Final Report

A STUDY TO CORRELATE SOIL CONSISTENCY LIMITS

WITH SOIL MOISTURE TENSIONS

by

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INTRODUCTION

The liquid and plastic limits of a soil are consistency limits that were arbitrarily chosen by Albert Atterberg in 1911. Their determination is by strictly empirical testing procedures. Except for the development of a liquid limit device and subsequent minor refinements the method has remained basically unchanged for over a half century.

The empirical determination of an arbitrary limit would seem to be contrary to the very foundations of scientific procedures. However, the tests are relatively simple and the results are generally acceptable and valuable in almost every conceivable use of soil from an engineering standpoint. Such a great volume of information has been collected and compiled by application of these limits to cohesive soils, that it would be impractical and virtually impossible to replace the tests with a more rational testing method. Nevertheless, many believe that the present method is too time consuming and inconsistent.

There have been numerous attempts to correlate devices to increase speed or consistency. There has been no general acceptance, to date, of any new device or method.

Since the case for keeping the limits in their present form is a strong one, and since they have proved valuable, the greatest need is for a device or method that will determine these limits with speed and "accuracy". They would have to be accurate in the sense of being consistent and having a high degree of correlation to limits produced by the present standard methods.

A method is presented here which meets the need specified above.

Research was initiated to investigate the development of a rapid and consistent method by relating the limits to soil moisture tension values deterimined by porous plate and pressure membrane apparatus. With the moisture tension method, hundreds of samples may be run at one time, operator variability is minimal, results are consistent, and a high degree of correlation to present liquid limit tests is possible.

The general objective of this research was the evaluation and development of the moisture tension method in light of its direct application to efficient use and greater economy by an organization required to determine limits in large numbers. Some organizations, such as state highway departments, make thousands of these tests each year.

This investigation has been limited to Iowa soils. Previously determined liquid and plastic limits were compared to values determined by moisture tension apparatus. The specific objectives of the research were as follows:

1. to confirm a relationship between consistency limits and soil moisture tension values;
2. to develop appropriate laboratory procedures for rapidly determining limit values of Iowa soils by moisture tension methods; and,
3. to establish a testing program of sufficient magnitude to determine the reliability of the results with a relatively high degree of confidence.

LITERATURE REVIEW

Early Research

Science can be defined as coordinated, systematized knowledge. In this sense, in the year 1911, Albert Atterberg initiated the science of measuring plasticity. He collected, studied and commented on twenty methods for measuring plasticity, or indicating its relative value, which had appeared in the literature at that time; and he found none of these methods satisfactory. He started with a conglomeration of previous concepts of plasticity requiring that a paste of "normal consistency" be prepared and formed into cylinders, balls, threads, rings or rods and be subjected to various manipulations, such as, reshaping, tensile and compressive strength tests, bending, rolling into a thread, extruding a thread from a hand press, and penetration with a Vicat needle. He classified the above methods under one group, that is, methods that make use of the clay in a plastic condition. Atterberg also categorized, and discarded as being a poor measure of plasticity, five other groups of methods; such as, methods that base the plasticity on the strength of the dry clay, methods that employ ability to adsorb water as a measure of the plasticity, methods that calculate the plasticity from the "binding power", methods that make use of the quickness of disintegration of the clay mass in water and methods that accept the idea that the colloidal content of the clay provides a measure of the plasticity.

To Atterberg, plasticity meant "capable of being shaped" and he put emphasis on the ability of a soil to be rolled out into threads. The result of his intensive studies, began in 1902, in the field of plasticity

led to five boundaries, or limits, to differentiate various plastic states of soil and to assist him in making an accurate study of soil properties.

In a comprehensive review of the history of the Atterberg limits, Bauer (6) summarized the five limits as follows:

1. the upper limit of fluidity, that is, the limit at which a clay slip is so watery that it flows almost like water;
2. the lower limit of fluidity, or flow limit, the limit of water content at which two small portions of a clay slip, lying in a dish, will no longer flow together with vigorous blows of the dish;
3. the sticky limit, the limit at which clay no longer is sticky;
4. the roll-out limit, the limit at which the clay paste can not be rolled into threads; and,
5. the cohesion limit, the limit at which damp clay will not allow itself to be compressed any more.

Bauer also summarized the more important conclusions of Atterberg's work:

1. the flow limit and the roll-out limit are the real plasticity limits. At water contents lying between these limits the clay is plastic;
2. that soil is plastic which, at or under the flow limit, can be rolled out into threads;
3. the difference between the values of the flow and roll-out limits - the plasticity number - is the best measure of the plasticity grade (or class); and,
4. that this method for the determination of plasticity is so

simple that it must find frequent use by others.

The flow limit is now the liquid limit; the roll-out limit is now the plastic limit; and the plasticity number has been changed to plasticity index. The liquid limit has been greatly refined. The plastic limit is determined, today, essentially in the same manner as it was by Atterberg. These limits, especially the liquid and plastic limits and associated plasticity index, have taken on great importance in almost all phases of soil engineering.

Atterberg's work appeared to provide the impetus that started many other researchers manipulating pastes of their own to change, standardize or explicitly define limits of plasticity. In fact, many researchers, working independently, probably sowed the seeds that created our present state of questionable standardization of the limits.

The agronomists were among the early researchers interested in Atterberg's work on plasticity. They seemed to want a less arbitrary measure of plasticity. In another history of early methods of measuring soil consistency, Bodman (8) presents a review of early research methods. Much of the work covered in his review is from agronomy literature and not generally found in engineering literature. Most of the methods proposed by the agronomists were based on the concept that, "consistency is the resistance to deformation of material", a concept that Atterberg initially discarded.

The methods reviewed by Bodman include: mixing by pug mill to measure resistance of a motor driven pug mill to soil-water mixtures; use of shallow, flat bottomed, glass cylinders in place of the curved evaporating dish and deforming the soil by means of weights rather than

than impacts; use of a similar approach in applying the weights to the soil vessel as it was on the platform of a Troemmer balance; and also, methods based on various penetration tests, compression of a stationary cylinder, compression and shearing of a prism or annulus, shearing of a cylindrical core, shearing a core from its surrounding mass in position in the field and in-place compression in the field.

Terzaghi (58) pointed out that Atterberg's liquid limit was an arbitrary one because there appeared to be no definite reason why the test should be made precisely as suggested. He discussed reasons for early opposition to Atterberg's work, and pointed out the following:

> "The striking difference between the attitude assumed by different investigators towards Atterberg's plasticity index is essentially due to two facts:
> (a) Failure to attempt to define clearly the meaning of 'degree of plasticity'; and,
> (b) The hopeless attempt to correlate with each other the plasticity of different substances."

After initial early attempts of the agronomists, they seemed to lose interest in the limits and reported research shifted to engineering literature. Baver (7), in a leading textbook on soil physics, only gives them passing mention. The plastic limit is roughly the upper limit of soil puddling, the point at which the soil is too wet for plowing, but no really important use has ever been found for the liquid limit. Agronomists, then, had no incentive to continue research on the consistency limits.

Other early research on Atterberg's limits more pertinent to engineering uses, was conducted at the Bureau of Public Roads (10, 24, 25, 52, 53, 57, 58) and the Bureau of Standards (28). Wintermyer, and his coworkers at the Bureau of Public Roads were largely responsible for

entrenching the concept of the consistency limits into the area of soil classification. They recognized the value of plasticity tests of subgrade soils. Hogentogler, Wintermyer, and Willis (25) placed prime importance on plasticity index as a measure of highway soils properties. They defined the liquid limit as the moisture content at which soil will just begin to flow when lightly jarred 10 times.

Early researchers used a spatula to produce the groove in the soil cake. The thickness of the cake was indicated as 3/8 inch, or slightly less than one centimeter; and the width of the groove at the bottom was usually given as 1/8 inch. First use of a grooving tool was reported by Wintermyer, Willis, and Thoreen (53). When A.S.T.M. method D 423 was first issued as tentative in 1935, provision was made for this tool and it has remained unchanged to date. It will be pointed out below that not everyone uses this standard tool, but no alternative has yet been officially adopted.

Arthur Casagrande (10) made a comprehensive study of the liquid and plastic limits. He designed a liquid limit device to mechanize the liquid limit test and remove the deviations that were due to operators' hand techniques. This apparatus is essentially unchanged today, except that, in a later research report, Casagrande (9) recommended minor improvements and initiated some small changes.

Casagrande (9) retained the hemispherical form of soil dish that Atterberg had used, but replaced porcelain with metal. He standardized the impact to cause a small momentum change, and he mechanized this impact. The device was then correlated to Atterberg's original work by standardizing the number of blows, "N", at 25.

Casagrande's device was essentially the same as now specified in the current tenative method of test for liquid limit of soils, ASTM Designation: D423-61T (3). A major exception is that the grooving tool developed by Casagrande has never been accepted as a standard or alternate, although it is widely used (32).

Casagrande also observed that the number of blows necessary to close the groove depended on the water content of the soil in the cup, and that when the results of a series of determinations for any one soil were plotted, water content versus the logarithm of the number of drops of the cup, the points fell on a straight line. This "flow curve" is required by the present method for determining the liquid limit of soils, ASTM Designation: D 423-61T, section 5 (3) states:

> "Plot a 'flow curve' representing the relationship between water content and corresponding numbers of drops of the cup on a semi-logarithmic graph with the water content as abscissae on the arithmetical scale, and the number of drops as ordinates on the logarithmic scale. The flow curve is a straight line drawn as nearly as possible through the three or more plotted points."

Casagrande (10) also noted that the slope of the flow curve varied for different soils and proposed that the slope of the curve be measured by extending the curve across one cycle of the semilogarithmic scale and securing the difference in water contents at 10 and 100 drops of the cup. He called this value the flow index, which is equal to the negative slope of the equation representing the flow curve, i.e.,

$$W = -F \log N + C \quad \text{---------- (1)}$$

Where:

W = moisture content in percent of dry weight

F = flow index

N = number of blows

C = constant

Based on this study, Casagrande concluded that Atterberg's liquid and plastic limit values, supplemented by the flow index, reflect the shearing resistance of a plastic soil in the remolded state at various water contents. In the case of non plastic soils, the relationship does not hold.

In his later work, Casagrande (9) revised his working drawings for the liquid limit device, making several changes in details without deviation from the original standards. The revisions called for the use of Micarta No. 221 for the base, whereas his original called for "hard rubber of quality which can be machined". (The present ASTM standard (3) calls for "hard rubber" without defining the term). He designed feet for the later model, as required by the ASTM standard, whereas his original device had none. The cam used to raise the cup 1 cm. above the base was changed from a spiral to, two concentric circles.

It is apparent that, as soon as the importance of the liquid and plastic limit tests was recognized the need for standardization and refinement of equipment and techniques was also recognized. The next section will be concerned with literature indicating a need for more consistent results and discussing sources of error in the present devices and procedures.

Evaluation of Present Devices and Methods

Recent research in the area of the liquid and plastic limits has been directed either at making recommended changes in present devices or methods, or proposing a new "machine" or device. Researchers search for a method or device that is simple and fast, as well as capable of producing consistent results free from operator variability. It is also essential that any new device be correlated to the present limits, due to the great volume of information presently based on them.

Sowers (49) compiled a list of faults of the present test that contribute to variation in the results:

1. difficulty of cutting a groove in some soils, particularly those containing sand;
2. tendency of soils of low plasticity to slide in the cup rather than to flow plastically;
3. tendency of some soils of low plasticity to liquify with shock rather than to flow plastically;
4. sensitivity to small differences in apparatus; such as the grooving tool form, the hardness of the base, the shape of the cam and the wear of the cup; and,
5. sensitivity to operator technique as the result of: groove shape and alignment, cleanliness of bottom of cup and base, speed of operation, observation of point of groove closing, lack of proper adjustment and thoroughness of mixing.

In addition to the above, there are liquid limit devices in use today that have hard rubber bases as specified by ASTM, and Micarta - 221

bases as recommended by Casagrande. The original bases had no "feet" but some operators cushioned the bottom. Later, the bases were supplied with feet, but there is no standard type of feet. There are three types of grooving tools, all which claim to have their relative merits, but they also cause differences in the limits, e.g. the Casagrande tool gives liquid limit values higher than those obtained by using the ASTM tool, but agreed well with the Hovánýi tool (32). Tool motion, whether away or toward the operator causes variation as high as 6 percent, and 3 percent on the average (32).

A brief comparison of the tools follows (32). The ASTM (standard) tool does not control the depth of groove, which is left to operator care and judgment. Casagrande's tool smoothes the soil to a specified depth, but it tends to tear the sides of the groove. The Hovánýi tool was designed to combine the "good" points of the two; that is, cut the soil to a controlled depth without tear. The Hovánýi tool seems to be considered "radical", but the first two are in wide use. Even though the ASTM tool is standard, a survey conducted by Section B, Subcommittee R-3, of ASTM Committee D-18 showed that the Casagrande tool is used by 4 highway departments, 1 government agency, 1 commercial agency, 10 experts and universities. The survey also quotes (anonymously) manufacturers: "Casagrande grooving tool outsells ASTM"; from another, "ASTM outsells Casagrande tool 4 to 1".

Mitchell (32) made a study of liquid limit results produced by the three different tools of which the ASTM and Casagrande are widely used.

The U.S. Army Corps of Engineers uses the ASTM tool in the determination of liquid limits of soils to be used for military construction

purposes and Casagrande tool in civil works construction activities. Some laboratories had used the two devices interchangeably, but began to question the results. The depth of groove made by the ASTM tool depends on operators judgment, but its main advantage is that it does not tear the groove, especially on soils of low plasticity. The Casagrande tool insures a constant depth of groove but tends to tear soils of low plasticity. The Hoványi tool was developed in an attempt to overcome the tearing action of the Casagrande tool. It has the capability of making smooth grooves relatively easily in soils of low plasticity. Mitchell (32) concluded that the tools should not be used interchangeably when testing for compliance with specifications.

Dawson (17) sent out uniform samples to nine commercial laboratories for liquid limit determination and tests for operator variability. Table 1 shows the results that were reported. One laboratory had a single technician run 20 tests on a single uniform sample over a period of about 7 weeks. His liquid limit values varied from 60 to 68.

Table 1. Liquid limit results reported by nine commercial testing laboratories

Sample	Average L. L.	Range
A	25	20-30
B	67	65-70
C	62	58-71

Tests were also run by students at the University of Texas and it was concluded from this study (17):

1. the liquid limit test (ASTM Method D 423-59T) is questionable and needs further study and investigation;
2. if it is to be continued, procedures must be revised and standardized;
3. under present test procedures variation in results range from $\pm$ 5 percent to $\pm$ 10 percent;
4. further investigations should be made to find factors that influence the liquid limit test procedure and to determine whether or not specifications can be written to control these factors; and,
5. inasmuch as the soil has a small but definite shearing strength at the liquid limit the author "wonders" whether it would be desirable to eliminate the liquid limit test entirely and substitute a shear test in its place, such as a standardized vane shear or a viscosity test.

In another program to evaluate the liquid limit test, two separate universities, independently and unknown to each other, were given new sets of both ASTM and Casagrande liquid limit devices (34). The authors state that, "it is known that in the extreme of variables the liquid limit on the same sample can vary as much as 30 per cent." The equipment used in the program was interchanged in four sets as listed below:

1. Casagrande base (Micarta 221) with Casagrande grooving tool;
2. Casagrande base, with ASTM grooving tool;
3. ASTM base (hard rubber) with Casagrande tool; and,

4. ASTM base, with ASTM tool.

Also tested was the effect of air drying versus oven drying of samples and the effect of moving the grooving tool away or toward the operator. Based on the results of the above tests, the following recommendations for change in the ASTM method were made:

1. air dry the sample to approximate plastic limit;
2. use distilled water in preparing the pat;
3. use ASTM grooving tool;
4. cut the groove with motion away from operator, from lip to center of cup;
5. use a Micarta 221 base; and,
6. use a metronome to insure a dropping rate of 2 blows per second.

Most of the research effort has been concerned with liquid limit devices. However the plastic limit method is not without supporters of proposed changes. Abun-Nur (1) states that in many loessial soils of the midwest, with low plastic limits, the rolling of a thread by ASTM method D 424 (2) is either impossible or does not provide reproducible results. He proposes that D 424 be replaced by a cube method that was originally devised by J. C. Russell of the agronomy department of the University of Nebraska and used for a time by the Nebraska Department of Roads. The cube method consists of molding a wetted soil into a cube of approximately 3/4 inch, then pressing and reshaping it until it dries to a moisture content where the cube develops cracks. Abun-Nur concluded that the two methods may be used interchangeably.

The soil itself can cause the consistency limits to vary. Winslow and Gates (51) made a study of the effect of rehydration on the Atterberg

limits. The authors presented two problems of standardizing the limits:

1. individuals commonly disregard certain parts of the ASTM standards when preparing a sample; i.e., samples are air or oven-dried or not dried, and the length of time samples prepared by either of the first two methods are allowed to rehydrate varies; and,
2. the current ASTM methods do not allow enough time for an air dried sample to approach equilibrium with the water added to make it plastic.

A study of the mineralogical composition of the soils was also made, and a correlation between clay mineral composition and the limits was evident. A summary of the authors (51) conclusions follows.

In four samples that did not contain montmorillonite as their most common clay mineral constituent, air dried material that had been rehydrated at a moisture content near the liquid limit or plastic limit for 24 hours generally had approximately the same Atterberg limits as material that had not been dried below field moisture content prior to testing. Because of the rehydration characteristics of montmorillonite, these soils have lower liquid limit and plastic limit if allowed to dry before testing, even after a 24 hour rehydration period. The limits are somewhat lower if rehydration is only allowed for four hours. and as much as 20 percent lower if only allowed for 30 minutes. The authors recommended a standard rehydration time of 24 hours for air dry samples before limit values are determined.

Sundolf, (50) in an earlier (1949) study of the effect of rehydration on the liquid and plastic limit tests, concluded that: soils containing

kaolinite, when allowed to stand wet for 24 hours, lose plasticity, expressed in terms of the Atterberg plasticity index; kaolinite soil should be tested no less than three hours after wetting; and, soils containing montmorillonite reach their maximum plasticity after about one hour of wetting. For maximum plasticity, therefore, an unknown soil should be tested at least one and no more than three hours after wetting.

Since these above conclusions do not appear to be directly supported by the later study (51), the results may be inconclusive. However, this situation does appear to emphasize that the effect of soil rehydration is a variable that must be considered in relation to standardizing the consistency limits of a soil.

During the recent, much publicised, AASHO road test, it was necessary to train several inexperienced technicians to make determinations of liquid and plastic limits. Shook and Fang (47) reported on a comprehensive test to study the variability which might be expected among these operators. They found that there was a significant difference between operators for both liquid and plastic limits.

Ballard and Weeks (5) used a carefully prepared artificial soil as a standard soil to study the "human factor" in plastic limit determination. They found that the major factor contributing to the total variance of results was the individual operator. Operator variance was further attributed to the decision that must be made regarding the end point of the plastic limit test. In other words, an operator was able to reproduce what he considered to be the plastic limit; however, there did not appear to be sufficient agreement between operators regarding the precise termination of the test. Plastic limit mean values between

17.1 and 23.1, a 35 percent deviation, were reported by different operators.

As a result of their study, Ballard and Weeks (5) recommended that a standard, artificial sample be specified for universal use of "calibrating" or checking operators. They also recommended a hydration time of 24 hours, which generally agrees with the recommendations of Winslow and Gates (51).

Liu and Thornburn (30) also made a recent (1964) study of the reproducibility of Atterberg limits. They conducted a statistically controlled experiment to investigate both how well an operator can reproduce the Atterberg limits, and the effects of the operator's experience. They concluded that the magnitude of the variations were relatively small, i.e., they can be regarded as reproducible from an engineering standpoint. They also concluded that an operators experience does affect variations, that the plasticity index value is most variable and the liquid limit value is least variable.

Krebs (29) presented data showing that a single operator could obtain appreciable differences in liquid limit. These variances were attributed to whether the soil was being moistened or dried between successive trials and on the amount of "spatulation" employed.

Development of Alternate Limit Procedures

Three principle objectives for correlating a new method to Atterberg's limits are simplicity of operation, speed, and obtaining results that can be reproduced within narrow tolerances.

In regard to one-point methods, there is no question regarding the

simplicity of operation because the equipment and general procedure are not changed. The idea of speed has considerable merit theoretically, because the method should be faster by a factor of 2 or 3. However, it is necessary for the result, "N", to be within a certain range. For a good determination N should be between 20 and 31 blows, with a range of 15 to 41 blows allowable for classification purposes (59). The time saving factor depends on "N" being on the acceptable ranges without many trials. The one point method can be only as accurate as the regular determination and is obviously going to be somewhat less accurate, because the method has all of the source of error inherent in the standard method plus an additional source, discussed below.

Most one point methods follow early work by the Corps of Engineers, Waterways Experiment Station (59). The method is based on the hypothesis suggested by Casagrande (10), that plotting both water content and number of blows to a logarithmic scale, might have a constant slope for soils of the same geologic origin. In general, flow lines of higher liquid limit values have steeper slopes than those of lower liquid limit values. On the other hand a log-log plot reduces the slopes of the higher liquid limit slopes more than it does the lower ones; it tends to equalize the slopes. Now, if it can be shown that the slope of the flow lines for soils in the same geologic formation is essentially a constant on a logarithmic plot, then the liquid limit can be determined from one test point for each soil. The flow line can be drawn through the point at the constant slope, and the 25 blow point interpolated as usual. The procedure can be summarized in a few steps. First it is necessary to determine a geological group. The Waterways Experiment Station used 3

groups:

1. the alluvial valley of the Miss. river,
2. the west Gulf Coastal Plain; and,
3. the East Gulf Coastal Plain.

A flow line is determined in the usual manner and its slope is determined and converted to a log-log plot by replotting the data. The slope is then determined:

$$\tan B = \frac{\text{Log } W_{10} - \text{Log } W_{30}}{\text{Log } 30 - \text{Log } 10} = \frac{\text{Log } \frac{W_{10}}{W_{30}}}{0.477} \quad \text{-----(2)}$$

where:

tan B = slope, referenced to the horizontal

W_{10} = moisture content at 10 blows

W_{30} = moisture content at 30 blows

W_{10} and W_{30} are determined from semi-log plot, with 10 and 30 blows being arbitrarily selected

The above method is not theoretically correct because, except for a horizontal or vertical line, a straight line on a semi-log plot will not be a straight line on a log-log plot; but the variation is considered to be of no consequence (59). Equations of the above type are usually reduced to the form:

$$LL = W_N\left(\frac{N}{25}\right)^{\tan B} \quad \text{----------(3)}$$

where:

LL = liquid limit

W_N = water content at N blows of the liquid limit device

tan B = slope of the flow line on a log-log plot (mean value for a given soil group).

The effect of change in liquid limit values due to variations in tan B can be determined by the method of differentials. The end expression for per cent change in liquid limit is (59):

$$\Delta LL_p = \frac{\Delta LL}{LL} \times 100 = \ln\left(\frac{N}{25}\right) \times \left(\Delta \tan B \times 100\right) \quad ----(4)$$

where:

ΔLL_p = change in LL, percent

ΔLL = change in LL

N = number of blows to close groove

tan B = slope of constant curve

Equation 4 may be used to determine a theoretical limiting range of blows for any percentage deviation from the liquid limit that is considered allowable.

The Waterways Experiment Station used the value, tan B = 0.121. Researchers who are concerned with this method usually determine their own value for tan B to best fit their particular soil group or conditions. Multicurve charts, special slide rules, nomographic charts and others (6, 18), are aids used by some to solve their particular form of the equation. For a more detailed account of one-point liquid limit determinations, Eden (18) traces their development in detail. He includes numerous references and an appended, "Suggested Procedure for One-Point Liquid Limit Determination."

ASTM Designation: D 423-61T, (2) includes an alternate one-point method. It states:

> "The accepted trial shall require between 20 and 30 drops of the cup to close the groove, and at least two consistent consecutive

closures shall be observed before taking the moisture-content sample for the calculation of the liquid limit."

The result is then used to calculate the liquid limit by the formula:

$$LL = W_N \left(\frac{N}{25}\right)^{0.12} \qquad \text{----------(5)}$$

Where:

N = number of drops of the cup required to close the groove at the water content, W_N.

A table of values of the factor $(N/25)^{0.12}$ is presented for "N" between 20 and 30 as a convenience.

Eden (18) discusses several values of tan B that have been proposed and used - 0.121, 0.135, 0.092 and 0.108. A suggested procedure is presented, along with the caution that his method assumes a flow line with a constant slope of 0.100 for all soils which is not "strictly correct." He concludes that the error can be neglected except:

1. where special accuracy is required; and,
2. for highly organic soils

The Ohio State Highway Department is one large organization that has adopted a one-point test (27). Ohio requires that the blows be in a range between 22 and 28. A special slide rule has been developed to convert the results, which are claimed to be, "as accurate as the 3 point method."

Development of Alternate Limit Devices

Penetration test devices are the only ones that have so far seriously challenged Casagrande's liquid limit device. In fact, they have been

adopted in certain countries. The penetration test is essentially a "compromise" of the concept, held by many soils engineers, that the liquid limit test is a measure of the viscous resistance, or shear strength of a soil that is so soft that it approaches the liquid state. A compromise because tests such as vane shear and direct shear, that have been used directly to measure the strength of soils at the liquid limit, require relatively complex equipment and careful performance; and this consideration tends to defeat the purpose of a simple, quick measurement of plasticity.

It is of interest to note that mention of penetration devices was made by early researchers. Bodman (8), referring to field testing, stated that soils were too variable to expect consistent results. Terzaghi (57) concluded that the relation between the yield point and penetration of a freely dropping cone is very different according to the nature of the material; and that results furnished by the test (consistency determination by penetration) may be misleading.

The penetration test device generally used is known as a "cone penetrometer." Its use as a measure of shear is based on a relationship between shear strength and penetration resistance of solids. This relationship is a constant in materials such as saturated clays regardless of the stress or strains imposed (49). There are three cones that have been developed and put into use: the USSR cone, the Indian cone, and the Georgia Institute of Technology cone.

Experiments with cone penetrometers have been conducted independently in at least four nations: USSR, Bulgaria, India, and the United States. Apparatus developed was similar, and results generally agreed. Sowers,

Vesic and Grandolfi discuss cone penetrometers and report in detail on work done in foreign countries, summarized as follows (49).

Early attempts in the USSR employed the Vicat needle and narrow cones. A standardized test was reported in 1949, consisting of a 30 degree cone and weights of 76 grams. Moisture content is determined at 10 mm penetration which indicates the liquid limit. When the results were plotted against ASTM method D 423-54T, they were the same at a liquid limit value of 15; above this value the cone value is lower. When the curve is adjusted to coincide with ASTM determinations (a usual procedure that goes with this method) results are claimed to be accurate within 2 to 3 per cent. This method has been adopted as a standard in Bulgaria and is widely used in the USSR and neighboring countries.

An Indian cone was also developed at the Indian Central Road Research Institute (49). It consists of a 31 degree cone, 1.2 inches long, mounted on a sliding stem with a depth indicator. It has a total weight of 148 grams and a penetration of 1 inch or 25 mm indicates the liquid limit. This cone shows good correlation for liquid limit of 25 or more. For lower values the cone penetrometer indicates a higher liquid limit than the ASTM standard method. In practice the limit has been taken as the moisture content at 1 inch penetration without any correction for the indicated deviation from the usual standard method. A one-point method has also been formulated where the water content for any penetration from 0.8 to 1.2 inches can be measured and converted to be equivalent to 1 inch penetration.

Sowers, Vesic and Grandolfi (49) followed a similar procedure and developed the "Georgia cone". The effect of varying cone angle, cone

weight, time, and soil water content was also investigated. The resulting apparatus has a 30 degree cone, 75 gram weight and the limit is taken as the moisture content at 10 mm penetration. A one-point liquid limit chart, or nomograph, was delineated for use with the apparatus.

During development of the Georgia cone, the following variables were studied:

1. allowing the cone to fall freely from the soil surface to its final penetration causes variable dynamic effects. Restraining the cone so that it took 10 seconds to reach final penetration gave consistent results. An additional 10 seconds was needed, in most cases, before the cone finally came to rest;
2. weights from 55 gram to 95 gram were used with a 30 degree cone. No particular advantage in consistency was found at any particular weight;
3. constant cone penetration does not yield a "true" liquid limit value; it is too high for low water contents and too low for high water contents. However, variation is considered to be very small; and,
4. no variation was found by varying the cone angle between angles of 30° and 40°.

Darienzo and Vey (13) made a study of vane apparatus as a possible device for measuring the consistency of remolded soils. A smaller size vane than ordinarily used in the field was used to measure the shear resistance of four different remolded clays as a function of water content. The authors obtained a straight line plot, on log-log scale, of percent water content versus vane shear. The pattern was similar to the one-point

liquid limit equation.

Using the above approach the following equations are presented (13):

$$\text{Liquid limit } (L_W) = W_c \, (c/0.59)^{\tan B} \text{ ----------(6)}$$

$$\text{Plastic limit } (P_W) = W_c \, (c/4.40)^{\tan B} \text{ ----------(7)}$$

where:

W_c = water content at given vane shear test

C = shear value obtained in vane shear test

tan B = slope of line obtained by plotting water content versus vane shear to logarithmic scale = 0.153

0.59 = average value of vane shear at L_W by standard method

4.49 = average value of vane shear at P_W by standard method

Three of Darienzo and Vey's most pertinent conclusions were (13):

1. the vane shear at the plastic limit is nearly a constant for all clays; therefore, the vane method provides a convenient tool for determining plastic limits;
2. for static conditions a more general definition of liquid limit would be the water content of the soil at a prescribed shear resistance; and,
3. the vane shear resistance may be accurately found at the liquid limit by the Casagrande method for non-sensitive, fat clays.

Theoretical Approaches to Plasticity

The liquid and plastic limits are arbitrarily defined by empirical methods. There has been much research concerning evaluation of the tests and devices. The great importance of the limits goes unquestioned; also,

the simplicity of their determination. Yet, until recently (4, 45) practically no basic research has been conducted in an attempt to define and evaluate the limits outside the environment of their empirical definitions; e.g., determine the limits theoretically, by equation.

However, some qualitative attempts to give theoretical definitions and concepts to the complex nature of plasticity had been presented earlier. As early as 1926, Terzaghi (57) suggested more study in relation to the meaning of the tests and the factors that determine their results. His writings on the subject were important contributions; however, they were primarily concerned with the significance of the tests. Casagrande (10) stated that the number of blows required to close the groove represented a measure of shearing resistance of the soil, and he approximated it at 25 gm. per sq. cm.

Hogentogler, Wintermyer, and Willis (25) stated that the shearing resistance of all soils at the liquid limit must have a constant value. They also defined the liquid limit state as the point where the soil particles are separated to such an extent that practically no cohesion exists between them, and related the plastic limit to:

1. the moisture content above which water evaporates about 4 percent faster from a clay sample than from a free water surface;
2. the moisture content at which the speed of evaporation begins to decrease;
3. the moisture content at which the coefficient of permeability of homogeneous clays becomes practically equal to zero;
4. a capillary pressure equal to 2.5 Kg/cm^2 acts on the sample; and,

5. the moisture content below which the physical properties of water are no longer identical with those of free water.

The plasticity index was generally considered a measure of cohesion. It was said to indicate the difference in water content required to increase the thickness of the water films separating the soil particles from the plastic limit to a degree such that the cohesion existing between them is reduced to practically zero (25). This last concept agrees with present concepts of modern clay mineralogists (22, 23). Croney and Coleman (12) relate the liquid limit to a negative pore water pressure of 4 gm. per sq. cm.

Davidson (16) described the liquid and plastic limit in terms of molecular attraction between the water and the soil particles:

> "---the liquid limit is that amount of water expressed in per cent dry weight of soil, which must be added to a soil in order that the water layers most distant from the soil particle surface acquire the properties of free water---"
>
> "---the plastic limit may be considered as that amount of water, ---, which must be added to the soil in order to provide a film around each particle of sufficient thickness to permit the particles to orient themselves and slide over each other, although still possessing cohesion in an appreciable amount."

The above definitions also follows the general concepts of plasticity as presented by modern clay mineralogists (22, 23). Most early attempts to theoretically define the true nature of plasticity are found in the ceramics and clay mineralogy literature.

McNamara (33) summarizes several of the theories regarding plasticity. Only the three which find some support today are included here as follows:

1. Colloid Theory. This theory is based on the fact that clays show marked similarity to colloids. Clays are plastic because certain colloids are present. The colloids thought to be

present in a clay are the hydrates of silica and alumina.

2. Molecular Attraction Theory. This theory states that a tough, viscous water coating is formed around each clay particle because of the attraction between the negatively charged (normally) clay particle and the positive portion of the water molecule (dipole). It is the viscous coating that allows the grains to slide when pressure is applied but holds them together in the absence of pressure. A broad interpretation of this theory could include the previous colloid theory.

3. Stretched Membrane Theory. Norton (35, 36) first presented this theory of plasticity. He attributes the force holding a clay "mass" (two or more particles) together to a stretched, unbroken sheet of water molecules around the mass. As the mass dries out, the water layers between the particles decrease and the surface membrane becomes thinner and pulls down between the particles to exert greater force. An analogy would be a toy balloon filled with dry pulverized clay and then evacuated, so that the pressure of the atmosphere presses on the rubber to hold the clay particles together. A change occurs; the dry clay in the balloon feels like a plastic clay-water paste.

Of the above theories, the molecular attraction theory is probably the most generally accepted. This theory is not essentially different from concepts set forth by Grim, from whom the following summary of concepts of clay mineralogy, relevant to plasticity, is taken. (All statements in the following eight paragraphs are attributable to Grim (22, 23).)

Certain components that may be present in soil materials may exert a tremendous influence on properties, even though they are present only in small amounts. The changing of such components by weathering processes, ground water movement, or construction activities could greatly change the properties of soil materials. Along with this delicacy, factors that control the properties of soil materials are:

1. the clay mineral composition - the relative abundance of the clay mineral components and their particle size distribution;
2. the non-clay mineral composition - the relative abundance of each mineral and the size grade distribution of its particles;
3. the electrolyte content - the amount and kind of exchangeable bases and presence of water soluable salts;
4. the organic content - the amount and kind; and,
5. miscellaneous textural characteristics such as shape of quartz grains, degree of parallel orientation of clay mineral particles and silification.

The important clay minerals are made up of unit flakes and aggregates of book like flakes. Much water is adsorbed on the basal plane surfaces of such units and is believed to have a definite orientation. In the first layers adsorbed on the plane surface, their configuration is such that it fits with that of the oxygen layers in the surface of the clay mineral units. The water molecules propagate themselves outward from the surface. A mass or sheet of oriented water molecules could be rigid, like ice. If so, the layers increase in thickness until, at some distance, the water molecules would no longer be oriented. At this point they become fluid, whereas the initially adsorbed water is not. When a group of

flakes are in close contact, the oriented water films, building independently from each surface, meet and form a rigid bond. With increasing amount, the point of "fluidity" would be reached and act as a lubricant between the flakes. It can be concluded from the above that a plastic condition would develop when the water supply is just in excess of all the rigid water that can develop. The change of water from the solid to fluid state can occur abruptly or gradually, but usually it occurs abruptly. This abruptness should cause a sharp break-point in plastic properties.

Tests show that it is extremely difficult to extrude clay through a die until some water is present. Also, the maximum compressive strength of sand-clay-water mixtures show that maximum strength is developed within very narrow moisture limits, which probably correspond to the maximum amount of rigid water that can be adsorbed. A time factor may be involved, as the compressive strength of some sand-clay-water mixtures increases gradually over short periods, which is probably the time of "rigid" water orientation.

Minor amounts of certain chemicals have a tremendous influence on properties of soil materials. For example, the viscosity of a sodium montmorillonite-water mixture is changed greatly by a trace of hexametaphosphate, small amounts of magnesium and boron alter clay bonding properties, and small amounts of sodium, hydrogen or aluminum greatly alter certain plastic properties. These above alterations can be explained in terms of their effect on the oriented water. For example, they alter the thickness of orientation, the perfection of orientation and the abruptness of transition to non-oriented water.

The plastic properties of a soil due to clay mineral effects, are largely a function of the kind of clay mineral. In regard to the Atterberg limits, kaolinite and illite have about the same effect and montmorillonite (Ca^{++}, H^{+}) has 3 or 4 times the effect of the first two. This highly plastic property is due to its tendency to break down into exceedingly small flake shape units, with a consequent tremendous amount of surface with particular ability to adsorb water between individual unit layers.

Mixing montmorillonite with other clay minerals produces some interesting effects. The mixture is one of discrete aggregates. The intimate interlayering that is affected causes much greater influence by the montmorillonite than the proportion would suggest. The reason for this fact is that kaolinite and illite occur in aggregate particles that do not come apart into much smaller units in the presence of water; but the montmorillonite forms planes of weakness, and relatively few such planes can cause a great dispersing affect.

Grim also discusses the Atterberg limits in terms of clay-mineralogy. There is no single plastic limit value that is characteristic of a particular clay mineral. Variations in the plastic limit are due to: exchangeable action composition, presence of non-clay mineral components, and inherent variations of structure and composition within the clay lattice itself. Based on unpublished work in his laboratory, he states that the plastic limits of some soils are increased by the presence of poorly crystalline amorphous material, while in other soils it may reduce the limits. The particle size of the clay minerals has a definite effect on the limit values. Limit values increase with decrease in particle size, with liquid limit tending to increase more than the plastic limit.

There are several size factors involved. The fineness of particles in the natural state is important. The degree of dispersion during sample preparation is also important. For example, montmorillonite particles are easily broken up in making a particle size analysis and the analysis may, indicate only the degree of disaggregation and not represent the particle-size distribution of the original material. Another factor is the perfection of crystallinity of the clay mineral components, with the smaller particles being less well ordered. Poorly ordered clay minerals break down into smaller particles more readily than well ordered minerals. A decrease in particle size would be accompanied by an increase in total surface. This increase would cause an increase in plasticity index. The "kind" of surface is also important, as the plasticity index increases much more rapidly for montmorillonite than it does for kaolinite, with illite and halloysite being intermediate.

As long ago as 1932, Casagrande (10) pointed out that drying could alter the plasticity of a soil, and numerous investigators have confirmed this fact. Drying of soils is accompanied by shrinkage, which tends to bring particles so close together that attractive forces become so great that water can no longer penetrate between them. It is known that removal of substantially all the water from montmorillonite, causing complete collapse of the structure, effectively prevents water from again entering between the particles. It generally takes more than air drying to cause such complete dehydration. However, drying with any vigor, tends to cause an irreversible change in clays of any composition, causing a reduction of limit values (22). To be truly representative of natural properties; therefore, limit values should be determined on undried samples.

Definitions of the consistency limits, after Grim (22), in light of the above theoretical concepts and related facts, are presented below.

The plastic limit is a measure of the water content just slightly in excess of the amount that a particle surface can adsorb in a highly rigid condition and which does not separate the particles enough to reduce attractive forces between them. The thickness of this rigid water would be in the order of 5 to 10 molecular layers. A completely unoriented water layer is not necessary for lubricating action (plastic state), it is sufficient that they are in a state such that their organization would yield under the application of a slight force. In addition to the water between particles, it is estimated that there is pore water present which probably ranges from about 20 per cent of the plastic limit value, in the case of montmorillonite, to a major part of some kaolinite clays.

The liquid limit is a measure of the water which can be held with any substantial rigidity, and does not separate the particles, but approaches the point where there is substantially no bonding force between them, (the verge of separation). This is the point where the relative abundance of rigid water decreases and the relative abundance of pore water increases, as compared to the plastic limit.

The plasticity index is the measure of the amount of water that can be added between particles, between the end point of rigid water and the point of particle separation, beyond which there is essentially no attractive forces between them.

The above discussion of the consistency limits from the clay mineralogy point of view, should emphasize the complex nature of plasticity, the difficulty of presenting theoretical explanations of Atterberg's

limits, and even the difficulty of obtaining consistant results with any device or method-"new" or "old". It may also explain why relatively little has been done to theoretically clarify the meaning of the Atterberg limits since the 1930's.

Some recent work is aimed at a better understanding of plasticity. The use of an activity value is a recent attempt (1953) to utilize the Atterberg limits to identify the nature of the clay particles present in a soil. "Activity" was proposed by Skempton (48) who suggested that since the plasticity of a soil is mainly attributable to the clay-size particles present in the soil, the activity may be evaluated by the expression:

$$\text{Activity of clay} = \frac{\text{Plasticity Index}}{\text{Percent clay sizes} < 2u} \qquad \text{----------(8)}$$

For any given clay, an approximately linear relationship exists between the plasticity index and the per cent clay sizes, and activity is the slope of the linear relationship. Activity values range from about 0.4 for kaolinite to about 5 for montmorillonite.

Skempton (48) found that the linear relationship between plasticity index and per cent 2u clay, passed through the origin. Seed, Woodward and Lundgren (45) found that the same relationship, for all clay types used in their investigation, was linear, but with the plasticity index becoming zero at a clay content of about 9 percent. This last relationship made it necessary to redefine the activity of clays as:

$$\text{Activity} = \frac{\text{Change in Plastic Limit}}{\text{Corresponding Change in Clay Content}} \qquad \text{------(9)}$$

By equation 9, activity is still the slope of the line, but by the formula:

$$\text{Activity} = \frac{\text{Plasticity Index}}{\text{C-9}} \quad \text{----------(10)}$$

where:

C = the per cent $<$ 2u clay sizes

The work of Seed, Woodward, and Lundgren (45), was done on artificial soils containing mixtures, in pairs, of kaolinite, illite and bentonite clay minerals. They concluded from the results, shown on numerous graphs with empirical equations of the plots, that the activity would accurately classify these soils with regard to their liquid limit versus clay content relationships, or their swelling potentials, regardless of the clay mineral composition of the clay fraction. It is suggested that the above relationships would also apply to natural soils. They further presented a lengthy discussion to support a hypotheseis that the activity of a clay would reliably reflect important engineering properties.

Ballard (4) made a comprehensive attempt to give a theoretical explanation and quantitative analysis to the plastic limit. He used carefully prepared artificial soils to eliminate unwanted variables.

Earlier work by Davidson and Sheeler (16) and Davidson and Handy (15) had concluded that the plastic limit decreases linearly with increasing clay content for clay values less than 30 per cent. Baver (7) reported in 1940 that in the higher ranges of clay content the plastic limit increases linearly with increase in clay content. Ballard reports others found a linear increase in the plastic limit with increase in clay content over a range spanning both the above mentioned ranges. The inference is that, "the plastic limit-clay content is not a simple linear relationship over the entire range of clay contents for all soils" (4).

Ballard (4) relates the variation of the plastic limit as a function of the clay content to the variation in bulk volume with respect to the weight fraction of fines for a two component packing system.

The packing diagram shown in Fig. 1 is used in ceramics to combine two sizes of grog (hard fired clay) and thereby reduce the pore volume (35). Line AB represents the volume of the solids that consists of various mixtures of fine and coarse particles. "D" is the bulk volume of the fine fraction and "C" is the bulk volume of the coarse fraction. Line CD represents the bulk volume of the unmixed (sum of individual total volume) fine and coarse components of various proportions. However, if the two are mixed thoroughly, the bulk volume will shrink to line COD, since the fine particles will fit into the pores of the larger ones. The theoretical minimum volume occurs at point "O" where the fine particles completely fill the voids of the larger ones, with the larger matrix still undisturbed; that is, the point at which the larger particles are on the verge of being pushed apart.

In practice, the bulk volume line of the mix depends on the ratio of the diameters, D coarse/D fine. Thus, the line COD (Fig. 1) represents an infinite ratio, whereas in practice a family of bulk volume curves such as H would be obtained. However, the basic equations of the hypothesis under consideration, were derived from the infinite ratio.

Ballard's primary hypothesis, therefore, is that the plastic limit is a function of the binary packing of clay and silt. As he states (4):

> "If the plastic limit of a soil is a packing phenomena such that the silt fraction of the soil behaves as a coarse fraction and the clay assumes the role of the fine fraction, then the theoretical plastic limit can be expressed in terms of the packing triangle. Assuming that the soil is fully saturated at the plastic limit,

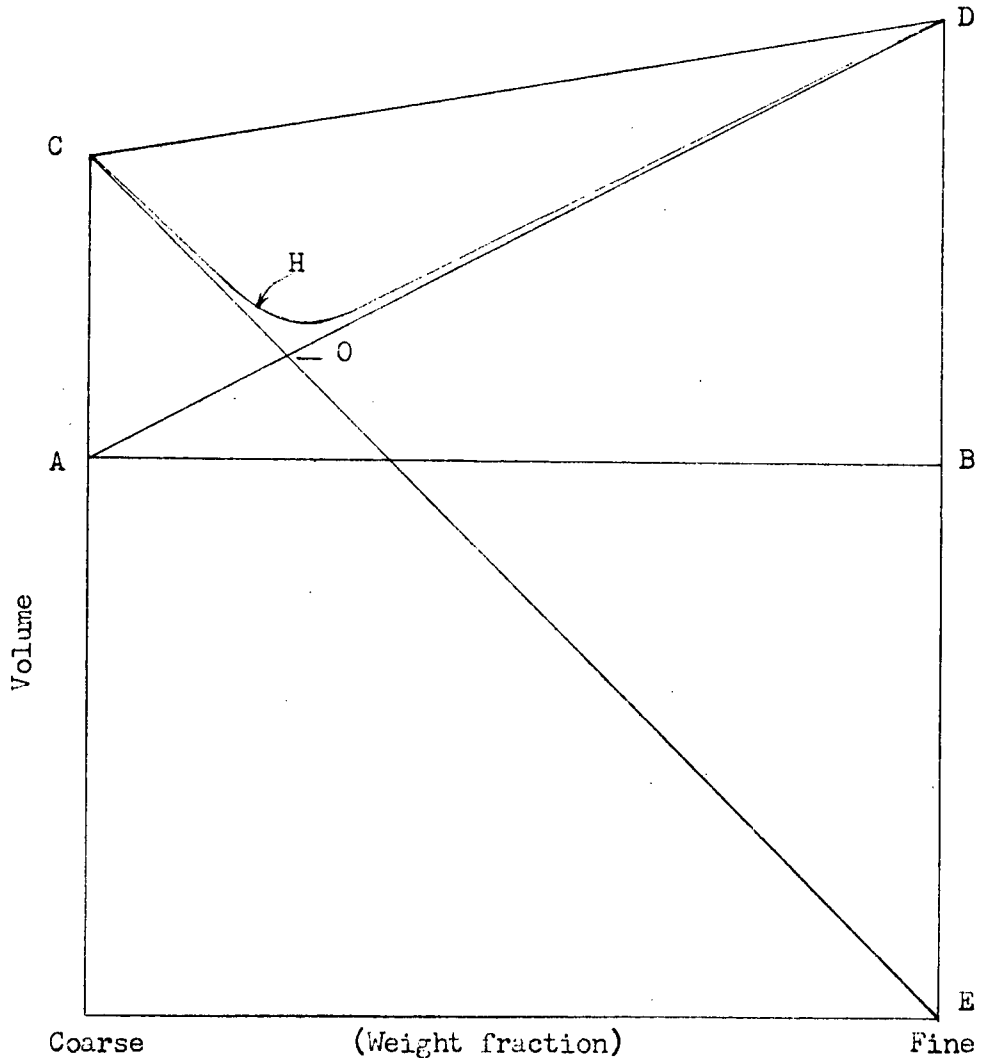


Fig. 1. Packing diagram of coarse and fine grog

then the plastic limit and water content, w, are measures of the pore space and hence the packing."

Ballard concludes that there are four distinct zones which completely define the clay-silt water systems, with the following pnysical concepts:

1. Zone A, represents the fine clay particles filling the interstices of the coarser silt fraction, which persists until the voids between the silt particles are completely filled with hydrated clay, but the system is non-plastic from a soil-mechanics point of view;
2. Zone B, represents the constantly expanding silt lattice, terminated when all the silt grains are separated from each other;
3. Zone C, represents hydration of the clay fraction in association with the silt to a level that it can sustain only while the silt lattice exists; and,
4. Zone D, represents random, dissociation of the silt particles without form or matrix, in a sea of hydrated clay.

Equations for the plastic limit of each zone were derived, based on the geometry of the packing diagram, void ratios, angularity, grading and packing constants of the silt and the specific gravity; as well as other assumptions.

In the "A" and "B" zones, occuring approximately from "C" to "O" (Fig. 1) plastic limit decreases with increased weight fraction of clay; in the "C" zone plastic limit remains constant, and in the "D" zone, plastic limit increases with increase in clay content. The "C" zone, occuring as a "transition" at "O" occurs between 40 to 50 percent clay. The "D" zone occurs approximately between "O" and "D". Ballard's work

is more complicated than may be indicated here. Quantitative equations are derived for the plastic limit in each zone and are expanded to include other silt variables such as angularity and packing of the silt grains.

Seed, Woodward, and Lundgren (46) used a very similar approach to develop a quantitative understanding of the consistency limits. The soil was visualized as being composed entirely of a clay fraction and a non clay fraction. The entire moisture content was considered to be associated with the clay fraction of the soil. A soil containing a high proportion of clay results in a mass which may be considered to have properties that are essentially the same as the clay fraction alone and it may be considered a series of non clay particles floating in the clay mass. (analogous to Ballard's Zone "D"). The liquid limit then depends solely on the liquid limit of the clay fraction and the proportion of the non clay particles.

This relationship is represented by the equation (46):

$$W_{LL} = \frac{C}{100} \cdot W_{CLL} \qquad \text{----------(11)}$$

where:

C = percent clay

W_{CLL} = liquid limit of the clay

W_{LL} = liquid limit of the soil

The same concept is applied to the plastic limit (46):

$$W_{PL} = \frac{C}{100} \cdot W_{CPL} \qquad \text{----------(12)}$$

where:

C = percent clay

W_{CPL} = plastic limit of the clay

W_{PL} = plastic limit of the soil

When the clay volume is less than the voids of the nonclay fraction allowing the non clay particles to come into contact, the equation is no longer valid. This point is calculated using void ratio relationships. The liquid or plastic limit at this point is taken as the lower limiting value. The point, given the notation C_{fv}, is calculated using specific gravity and void ratio data:

$$C_{fv} = \frac{X}{100 + X} \quad 100 \qquad \text{----------(13)}$$

where:

$$X = \frac{100 \quad e_L}{G_{sg}\left(\frac{1}{G_{sc}} + \frac{W_{CLL}}{100}\right)} \qquad \text{----------(13a)}$$

e_L = void ratio of nonclay fraction of soil in loosest condition

G_{sg} = specific gravity of nonclay fraction of the soil

G_{sc} = specific gravity of clay fraction of the soil

W_{CLL} = liquid limit of clay fraction

Or, in the case of the plastic limits W_{CLL} is replaced by W_{CPL}. Ballard (4) had derived an analogous equation for this point.

$$\bar{X}_v = \frac{\bar{e}c}{\bar{e}_c + \bar{e}_f + 1} \qquad \text{----------(14)}$$

where:

$\bar{X}_v$ = volume fraction of clay (fines)

$\bar{e}_c$ = void ratio of silt (coarse)

$\bar{e}_f$ = void ratio of clay (fine)

In deriving Equation 14, Ballard assumed that the specific gravities of the two materials were equal.

Seed, Woodward, and Lundgren (46) further point out that very

fine-grained nonclay soil particles may be sometimes induced to roll into threads. The plastic limit, may be expected to increase from the minimum value at the clay content C_{fv}, to a value representing the pure nonclay fraction. This state is analogous to Ballard's Zones A and B, which include the regions that decrease from the pure nonclay plastic limit to the point where the hydrated clay is just sufficient to completely fill the non clay voids. Seed, Woodward, and Lundgren (46) point out that there is likely to be gradual transition from the decreasing to the increasing region. This transition is analogous to Ballard's Zone C which is also a transition zone.

Both of the above authors extended their theoretical relationships to other characteristics of the soil mass. Other equations are derived. The above work was reviewed here briefly because it must be considered a great leap forward toward understanding the fundamental nature of the liquid and plastic limit.

Development of Moisture Tension Apparatus

In the agricultural and soil physics fields, a great quantity of literature is available on the energy relationships of the soil water system. Some of the energy concepts of soil moisture have been introduced in the soil engineering field.

It is not within the scope or objective of this thesis to analyze the soil water system or energy relationships. However, the equipment used in this study is based on these concepts, and it was developed to facilitate their study through better research techniques and equipment.

Richards (39, 40, 41, 42) was responsible for developing modern

moisture tension apparatus. It is used extensively in the agricultural fields for measuring the capillary potential of soils. It is now generally accepted that over a certain range of soil moisture, water in porous cups filled and connected to a manometer will come to a pressure equilibrium with a soil. In a similar manner, the moisture content of a soil on a porous plate or membrane will attain a steady value if a constant pressure differential is maintained across it.

Richards (39) pointed out that pressure difference across a porous wall or membrane has been variously termed suction, pressure deficiency, capillary tension and soil moisture tension. Also, early literature referred to the curves obtained by the relationship, moisture content versus soil moisture tension, by various names: sorption curves, characteristic curves and retention curves. The term "sorption" had sometimes been misused in the case of a drying curve, and Richards proposed the term sorption for soils increasing in water content (wetting curve), and the term desorption for soils decreasing in water content (drying curve).

Mickle (31), as part of a comprehensive history and development of energy relations of the soil-water system, explains the above wetting-drying relationship, along with hysteresis effect, well and simply:

> "Curves showing the relationship between soil-moisture tension and moisture content may be obtained either by wetting a dry soil or by drying a wet soil. The curves thus obtained are called sorption and desorption curves, respectively. In either case the process is controlled so that incremental soil-moisture contents can be measured. The sorption curve will usually give lower values of moisture tensions than will the desorption curve. The extent of this hysteresis effect is governed for the most part by the fineness of the soil; the finer soils exhibiting a greater hysteresis effect."

Much of the early work in the areas of soil-moisture has become

common knowledge found in almost every book or text covering soil water relationships. Baver (7) presents a very comprehensive treatment with 6 pages of references. The following information in this section, except where specifically noted otherwise, is essentially after Baver's text.

Capillary water is defined as the water which is held by surface forces as a continuous film around the particles and in the capillary spaces. Capillary potential is defined as the work required to pull a unit mass of water away from a unit mass of soil. Thus, when a pressure difference (suction or pressure) is required to extract water from soil, the amount of water in the soil is a function of the energy with which the water is held. Also, the energy required to remove water is a continuous function of the moisture content; i.e., a given energy will remove a given amount of water and come to equilibrium. A drier soil then, requires additional energy to remove additional water. When the equilibrium condition of the soil has been reached, the soil has a potential at that point equivalent to the suction (or pressure) applied. Size of particle and state of packing have a large affect on moisture content at any given capillary potential. Fine textured soils have a relatively larger number of contacts than coarse textured soils. The amount of moisture at each of the contact points is thereby reduced, affecting a corresponding decrease in the radius of curvature of the water menisci in the pores. Finer-textured soils, therefore, contain more water at any given potential.

When moisture content is plotted against capillary potential, a moisture-tension curve is obtained. These curves have a simple form

which raises the probability that only a small number of parameters are required for their representation. Also, because of this fundamental simplicity, there should be the possibility of expressing the capillary-potential-moisture relationship in terms of definite soil physical properties. The energy that must be expended to remove water from a soil, from saturation to dryness, is apparently a continuous function of the moisture content. Baver cautions that it does not necessarily follow that there is no change in the nature of the factors responsible for the attraction and retention of water somewhere along the curve.

It should be pointed out that the plot of moisture content versus "tension" may be expressed in many ways. Moisture content is expressed in three ways: percent by volume as generally used in agronomy, percent by weight as generally used in engineering and percent saturation. Tension may be expressed in centimeters, inches or feet of water, atmospheres, bars (1 bar = 10^6 dynes/cm^2 = 0.987 atmospheres) or pounds/in^2. To cover a wide range of pressures, the tension is usually plotted on a log scale. There is no definite convention regarding whether the tension is plotted on the abscissa or ordinate, but it is usually the latter.

The porous plates and pressure membranes themselves were developed by Richards (39, 40, 41, 42) as a better method to obtain the moisture-tension curves, particularly in the range of 1-15 atmospheres pressure equivalent. A domestic-type aluminum pressure cooker serves at pressures up to 2 atmospheres: higher pressures require pressure-membrane apparatus. This equipment will be described and pictured more fully in a later section.

Fukuda (20) made a theoretical and experimental analysis of the

process of extracting soil moisture in pressure-membrane apparatus. The reader who is interested in a mathmatical analysis of the mechanism is referred to the paper. Of more concern here are his conclusions concerning the effect of air humidity and temperature outside of the apparatus on soil moisture in equilibrium with various pressures inside the apparatus. He concluded that the effects of air humidity and room temperature outside the apparatus were of little importance.

Application of Moisture Tension to the Consistency Limits

The relationship between soil moisture tension and the consistency limits of a soil was investigated by Rollins and Davidson (43). A separate relationship was established for each textural group, as preliminary tests had indicated that this procedure gave the best results. Moisture tension curves were plotted and appropriate soil moisture tensions were approximated. Tests were then made at pressures near the approximate pressure until one was found that gave results with the least deviation from those that had been predetermined by the standard method. Table 2 shows a summary of their results.

Based on the above study, it was concluded that if the textural classification is known, the consistency limits can be estimated by assuming them equal to an appropriate moisture tension. The moisture tension pressures they recommended are those presented in the table below. They also compared their deviations, qualitatively, with the tabulated results of a comparative test by several different highway departments for consistency limits of one soil, and concluded that their results were within deviations that could be expected by conventional methods.

Table 2. Summary of results of Rollins and Davidson (43)

Textural group	L.L. tension (in. of H_2O)	No. run	Average deviation	P.L. tension (in. of H_2O)	No. run	Average deviation
silty loam	60[a]	22[a]	1.50	168	12	3.46
silty clay loam	60[a]			415	12	3.14
silty clay	15	16	2.56	913	15	2.58
clay	6	16	1.75	1650	12	2.34

[a]Combined in one test run.

A recent (1964) article in an English periodical (38), reports on the use of the relationship between soil moisture and suction as a new method of determining the plastic limit of soils. Both sorption and desorption curves are used, and the absence of hysteresis at a pF value at 0.5 is taken as the criteria of a non-plastic soil. Otherwise the plastic limit value is taken as the "---moisture content held by the soil against a pF of 0.5 on the wetting curve or 1.5 on the drying curve of the soil-moisture suction relationship,---" the term, pF, is the same as the log of the tension in centimeters of water. It is the same as "log-tension" which is a term sometimes preferred.

DEVELOPMENT OF THE MOISTURE TENSION METHOD

Equipment

The equipment developed by Richards (39, 40, 41, 42) is patented in the U.S. and available commercially. For many years agronomists removed water from soil, by creating a pressure difference, by suction, across a porous ceramic material which served as the link between the soil water and water outside. Pressure membrane and pressure plate extractors are a modification of this principle. By an applied pressure inside the chamber of the apparatus, a pressure difference is maintained across a porous plate or membrane, the bottom of which is at atmospheric pressure.

The apparatus, as used for this project, is pictured in Figures 2 and 3. A compressor was used as the source of air pressure for the pressure membrane apparatus; the university air supply was used as the air pressure source for the pressure plate apparatus.

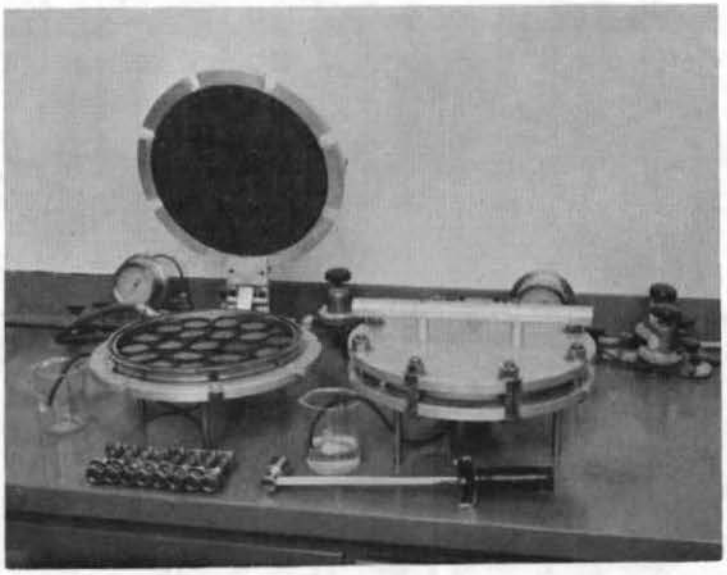
The pressure plate extractor is used in the low ranges of pressure, such as, 0-1 atmosphere. An excellent description is given in the manufacturers' catalog (54):

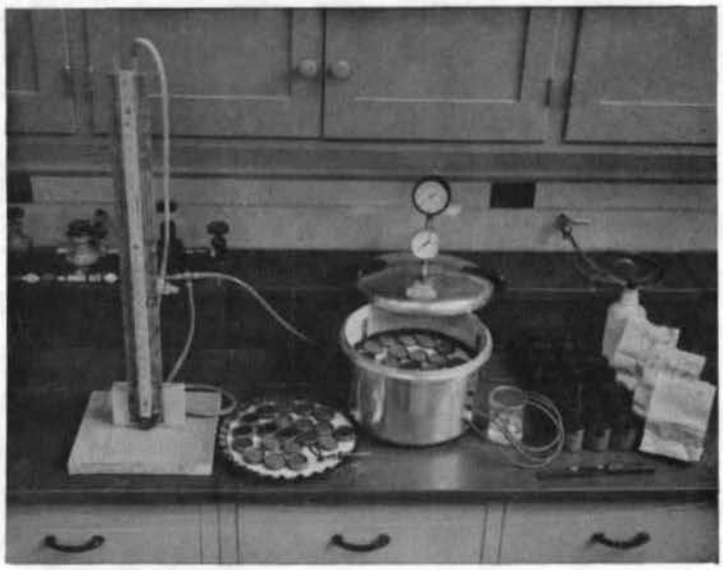
> "---The extraction is accomplished by means of special ceramic plates, called 'Pressure Plate Cells', operating in a pressure chamber. Each Pressure Plate Cell consists of a carefully manufactured ceramic plate which is sealed on one side by a thin neoprene diaphragm. An internal screen keeps the diaphragm from close contact with the plate and provides a passage for flow of water. An outlet stem running through the ceramic plate connects this passage to an outflow tube.-----. After loading with samples, the Pressure Plate Cell is mounted in the pressure chamber and subjected to air pressure. The pores in the ceramic plate are so small that they are sealed to air by the water films up to air pressures in excess of 1 atmosphere (15 psi). Water, however, will pass freely through the plate. When air pressure is applied to the chamber, moisture from the soil sample flows through the ceramic plate, then between the rubber diaphragm and

Fig. 2. Pressure plate apparatus, with ceramic plate loaded for a test run, and mixing materials (Top)

Fig. 3. Pressure membrane apparatus with one membrane loaded for a test run (Bottom)

(see next page)





> the plate, and up through the outlet stem and connecting outflow tube in the outside of the pressure chamber. At equilibrium, there is an exact relationship between the soil suction in the samples and the air pressure in the chamber.-----"

The pressure membrane apparatus operates in the same manner and uses the exact same principles. It has obvious physical differences which affect minor changes in its operation. The cross section of the apparatus, (Fig. 4 top) clearly shows its structure. A cellulose membrane, used instead of the ceramic plate, is laid over a screen covered drain plate and sealed with "O" rings. Compressed air is admitted to the extraction chamber through a cylinder fitting. The top fitting and compressing diaphragm were not used in connection with this study.

The pressure membrane apparatus is needed for using higher ranges of pressure than the ceramic plates can withstand. Soil moisture may be extracted up to around 15 atmospheres, or 225 psi. The pressure is the upper limit for which the equipment is guaranteed. However, the cellulose membrane has an average pore radius of 24 angstroms, and the theoretical upper limit is about 1500 psi. (55).

Fig. 4 center represents a soil sample on a cellulose membrane. The same figure could be used for a porous plate by replacing the membrane and screen with a porous ceramic plate. As soon as the pressure inside the chamber is raised above atmospheric pressure, water is forced through the microscopic pores in the cellulose membrane. Water will flow through a pore in the membrane until the radius of its meniscus decreases to a value small enough so that the force of the applied pressure is equalled according to the relationship:

$$p = 2T/R \qquad \text{----------(15)}$$

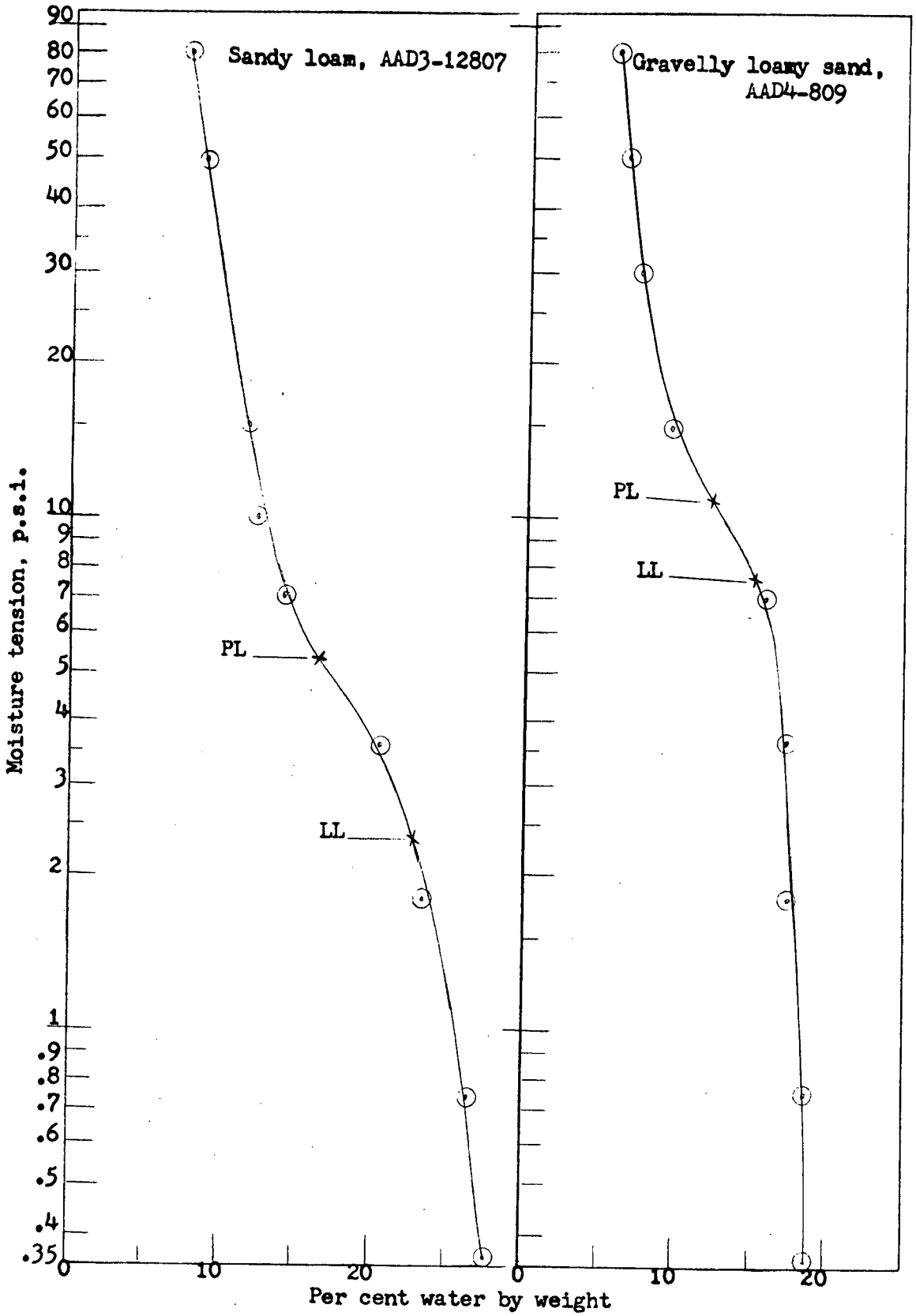


Fig. 22. A sandy loam and a gravelly loamy sand

Left. A sandy loam representing the group
Right. A gravelly loamy sand representing the group

where:

p = applied pressure

T = surface tension of the liquid

R = radius of the meniscus

The air pressure is held back by surface tension of the water at the gas-liquid interface at each of the pores, which will hold throughout the range of the apparatus. Fig. 4 bottom shows relative examples of a pore at three different pressures. At any given pressure, soil moisture flows around each soil particle and out through the cellulose membrane until the effective curvature of the water films throughout the soil are the same as the pores in the membrane, which will be in equilibrium with the given pressure. As the equilibrium state is reached, flow ceases. A pressure increase will resume the flow until a new equilibrium is reached.

Materials

The soil samples that were used came from two sources. During the first stages of the project, which consisted of establishing families of moisture tension curves for several textural groups, stored soil samples from the basement of the engineering experiment station laboratory were used. These soils had been sampled from almost all sections of Iowa, starting in 1950, under IEES project 283-s. The testing and research program was conducted as part of HRB project HR-1, "The Loess and Glacial Till Materials of Iowa; an Investigation of Their Physical and Chemical Properties and Techniques for Processing Them to Increase Their All-Weather Stability for Road Construction." Several hundred samples were analyzed over a period of years and their properties were recorded as a

permanent record and a sample of each was stored. The consistency limits were taken from their records and used for comparing the moisture tension results. It has been pointed out that since these limits were determined by several operators, they should be expected to vary (43).

The second phase of this project consisted of taking approximate pressures from the curves and making test runs to obtain samples at a moisture content that correlated best with one of the limits. Most of the soils for this second phase were obtained from the Iowa State Highway Commission Soils Laboratory. The sample obtained was a 100-200 gram "left over" portion of the same soil that their technicians had sampled, processed and tested. Their consistency limits were used for correlation. The commission's consistency limits are determined by a regular crew of four men who do no other work. It should be reasonable to expect that results produced by a steady, "professional" crew such as this, are going to be as free from human variance as possible.

The most significant parts of the mechanical analyses of the samples were recorded and are included with the tables presented herein. The complete record of these soils is kept by the commission for several years.

The portion of the soil used in this procedure is the minus No. 40 sieve fraction. The IEES soils had to be ground and sieved prior to being used. In the case of the ISHC soils, only the minus No. 40 fraction was obtained; no further preparation was necessary.

The sample origin may be noted by the numbers used in this thesis. All soils obtained from the commission are preceded by "AAD". All other numbers indicate soil samples from the engineering experiment station.

All mixing was done with distilled water.

Laboratory Investigation

The investigation essentially consisted of two "phases". The first phase consisted of finding representative curves for several textural groups. To obtain such curves, by desorption, it is necessary to bring an initially saturated soil to equilibrium at each of several different, increasing pressures. Each sample was split into as many parts as needed so that one could be removed from the apparatus after equilibrium was reached at each pressure. The moisture content was determined in the usual manner (oven dried at 105°C). The objective of this phase was to determine a representative curve for each textural group that could be used for determining the pressure that would equilibrate a soil of that group at a moisture tension that would approximate one of the consistency limits.

At the start of the project, the soils were saturated in accordance with procedures outlined in U.S.D.A. Handbook No. 60 (60), as suggested by previous work (43):

> "Approximately 30 grams of a representative sample of the soil was placed in a one-half pint fruit jar, and sufficient water was added at one time to bring it nearly to the saturation point. Where a large number of samples was being prepared, as many jars as needed were lined up in a row, and the soil was placed in them. Sufficient water was then added to each sample to bring it nearly to the saturation point. Each sample in turn was then brought to the saturation point, by slowly adding more water and mixing with a spatula.
>
> To determine the end point of saturation, the soil mass was transferred to one side of the jar. If the soil slowly flowed when the jar was tipped to an angle approximately 60 degrees with the horizontal, saturation was assumed. The jars were then capped, and the samples were allowed to stand for an hour or more, after which they were again checked for saturation. The saturated soil

was then placed in the rings* of the saturated porous plates."

Rollins and Davidson (43) stated that the above saturation process must be followed carefully because the soil moisture tension at each of the limits is affected by the initial moisture content. As the present work progressed, the above procedure seemed to be unnecessarily time consuming as well as arbitrary. A brief test was run to check the variation of moisture tension values caused by a variety of initial conditions. The results are shown in Table 3.

Table 3. Results of varied initial moisture content on a clay soil sample run at 20 inches of water pressure for 3 days

Sample	Wt. g.	H_2O added g.	Moisture at 20 in. H_2O A[a]	B[a]	Comments
1	15	0	56.41	56.37	air dry
2	15	5	43.74	41.05	compacted
3	15	10	53.07	51.87	"normal" (USDA)
4	15	15	56.64	56.38	free flowing
5	15	20	57.81	56.64	liquid
6	15	20	56.29	57.24	mechanically mixed, 20 min.

[a]Samples in column "A" were mixed, and placed on the plates to stand overnight in an excess of water (usual procedure). Samples in column "B" were left in capped jars and put on plate immediately before pressure was turned on.

Sample 2 approximated an optimum moisture condition, which is the reason that it had to be compressed (compacted) to conform to the mold; thus, the low value could be expected. It appears that the normal, or the condition obtained by the USDA method would be the most critical, and that if it were on the dry side, some compaction could possibly occur

*Rings used were approximately 3/8 inch in height

when placing the sample in the rings.

The test was probably not sufficiently comprehensive to warrant making definite conclusions on its basis alone. However, since a liquid state slightly wetter than obtained by following the USDA procedure can be placed in the rings with more speed and ease, can be arrived at least as easily and consistently (with experience) and could possibly be in a less critical region; the procedure was so modified. The saturation point used, therefore, is best described as the point where the soil mass could be slowly poured out of the jar, with care being taken that it was not so wet as to have free water on the surface when standing. The length of time that the wet soil had been kept in the capped jar made relatively little difference. Thus, for convenience as well as greater assurance of saturation, the mixed soils were left longer in the jars. Four hours was chosen as a minimum.

It can also be noted from Table 3 that the air dry soil, placed on the plate immediately prior to turning on the pressure, reached equilibrium by sorption, i.e., taking up water from the plate. On some early silty clay runs it appeared that the samples were taking up water in the region of the two lowest pressures; one possible explanation is that they were not really saturated to begin with. Points that were rerun using the modified, wetter initial condition, eliminated this tendency from these soils and all future runs. (A curve showing this tendency will be presented in the following section as Fig. 10.) It is not suggested here; however, that the initial condition makes no difference. A consistent initial condition could be very important, and emphasis was placed on being consistent.

As an initial step, the ceramic plates or membranes were always thoroughly saturated with distilled water. The saturated samples were allowed to stand on the plate (or membrane) in an excess of water, for 16 hours while covered with small squares of waxed paper (55, 56). Paper and excess water were removed prior to the run. Here again, the steps were abbreviated for convenience and ease of operation. Again, the emphasis was placed on being consistent. The procedure arrived at and used for all the later calibrations is as follows.

The samples were mixed and allowed to stand in capped jars according to the modified procedures above and then placed in the rings on the plate (or membrane). An excess of water, an approximate depth of $\frac{1}{4}$ inch, was placed on the plate. The apparatus was closed in readiness for a run. The samples were allowed to stand, without waxed paper covering, at least 16 hours. In practice, for convenience, they were generally placed during the afternoon and left set until the following morning. Then the pressure was turned on and the run started without attempting to remove any excess water from the plates. (Under pressure, the excess water comes rapidly out through the outflow tube.)

Rather than setting the end point, equilibrium, as a function of time, it was determined by the complete cessation of any sign of moisture flow from the outflow tube. This determination was made by wiping the tube dry and then laying it on a dry surface for at least an hour. If no water drop was observed, equilibrium was assumed.

According to the instruction manuals (55, 56) samples may be removed anytime after 48 hours, or earlier if the outflow indicates that equilibrium has been attained. It further states that most soils will approach

equilibrium in 18 to 20 hours. This was found to be the case in all but the clays, and some silty clays, which sometimes required up to 60 hours.

Except for the period when equilibrium was being checked, the end of the outflow tubes were kept constantly under a small amount (±1 inch) of water in a beaker. This procedure insured outflow into a constant environment as far as humidity was concerned. It also served as a check against air leaks.

Using the above method of end point determination, it was sometimes unavoidable that samples were left at equilibrium longer than necessary, perhaps over a weekend or even longer. Another test was run to study the effect of leaving a sample at equilibrium for several days. A sample was split into 9 parts and taken out in pairs (except the last), after 1, 3, 5, and 6 days at equilibrium. The results can be seen in Table 4. The lowest reading, at one day, is probably due to the sample not being in complete equilibrium.

Table 4. Results of splitting sample 45-1 and varying lengths of time in apparatus at 10 psi. (loaded samples and set at 10 psi on July 21, 1964)

Date	Sample 1 % moisture	Sample 2 % moisture	Average	Change from previous date
July 22	32.16	32.14	32.15	----
July 23	31.60	31.57	31.59	0.44
July 25	31.58	31.62	31.60	0.01
July 27	31.63	31.61	31.62	0.01
July 28	31.62	-[a]	31.62	0.00

[a]Only one remaining.

The effect of splitting a sample can also be approximated by the data in Table 4. This test is also not comprehensive enough for making quantitative conclusions with a high degree of reliability. However, the closeness of the results indicates that splitting the sample should not cause any major problems. This assumption proved to be true throughout the second phase of the project when all determinations were made in pairs. Almost without exception, every major deviation between the pairs was traced to a weighing or calculation error, or an obvious mixup of sample numbers.

After some initial trials, it was determined that a minimum of 8 pressures (10, 20, 50, 100 inches of water and 15, 30, 50, and 80 psi) were needed to obtain a good curve. Later, a 9th was added at 192 inches of water. Also, on some runs a point was obtained at a pressure of 10 psi. The pressures up to 192 inches of water were determined with the pressure plate apparatus; the higher pressures were run in the pressure membrane apparatus. Each run made with about nine different soils. One pressure membrane extractor was used to run samples at 15 and 30 psi; the second was used to run samples at 50 and 80 psi. All the lower pressures, inches of water, were run on the four plates of one pressure plate extractor. On occasion it was not readily apparent how to draw one of the curves, and additional points were made by separate runs to clarify the curve shape.

All samples were loaded together. Each soil had one sample available to be taken out as equilibrium was reached, in turn, at each of the pressures. The sample was removed at each equilibrium point, weighed and placed in the drying oven. After the last sample was completed, dried

and calculated, a curve was drawn for each soil. It was decided that the best plot to clearly cover the range of pressures used, without distorting either the high or low range, would be obtained by using semi-log paper and plotting the pressures in pounds per square inch on a 3-cycle logarithmic scale as the ordinate, and the moisture content in percent on an arithmetic scale as the absisca. Typical curves, both single and composites for each textural group tested, were drawn.

The second phase of this project consisted of running a group of different soil samples at a specific pressure that would affect equilibrium at a moisture content that corresponds to one of the consistency limits. The curves proved to be too variable to pick a specific point with any confidence. The picking of a pressure turned out to be a trial and error procedure. After a few trials, it became evident that the curves could be used only as a rough, first approximation. The running procedure was exactly the same as it had been for the first phase of the project. The only variation was that each soil sample was run as a duplicate. Since every indication showed that the results of the duplicates should have been practically identical, or very close, it served as the only check against errors in weighing or calculating, or a mixup in sample numbers.

PRESENTATION AND DISCUSSION OF RESULTS

During the first phase of this project, data was obtained for the purpose of plotting moisture tension curves. The theory of soil moisture-energy relationships is beyond the scope and objective of this thesis. However, a brief discussion of some of the factors that affect moisture tension curves will give a clearer understanding to those presented here.

Figures 5 and 6, and their interpretation which follows here, are after Baver (7).

In Fig. 5 the effect on desorption of two layers of different size particles is shown. In curve A, fine particles (150 - to 270 - mesh) are placed in a layer over a layer of coarser (40 - to 60 - mesh) particles. Curve B has the layers reversed; i.e., coarse over fine. The curves demonstrate the validity of the generally accepted concept that the drainage of a pore is limited by the size of the neck.

To quote Baver (7):

> "In both curves in this figure (5) the dashed lines indicate the tensions at which the individual separates would drain. The curve A indicates that no appreciable amount of water was removed from the system until the tension necessary to start the drainage of the 150 - to 270 - mesh layer was reached. However, when this point was attained, a large percentage of the water was removed from the system with very little increase in tension. It is natural to suppose that there were a few pores larger than the rest in the 150 - to 270 - mesh and that they formed continuous passageways down through the layer as soon as the tension of the largest pores of this layer was reached, the meniscus was pulled through and an air passage down to the 40 - to 60 - mesh layer was established. When this occured, the 40 - to 60 - mesh was drained out immediately leaving the saturated stratum of sand above.-------The curve B shows that the 40 - to 60 - mesh sand drained out through the fine layer at approximately its normal tension. When the coarse layer had been drained, it was necessary to raise the tension before the fine layer drained. The difference between the solid and dashed lines is undoubtedly due to slight variations in packing."

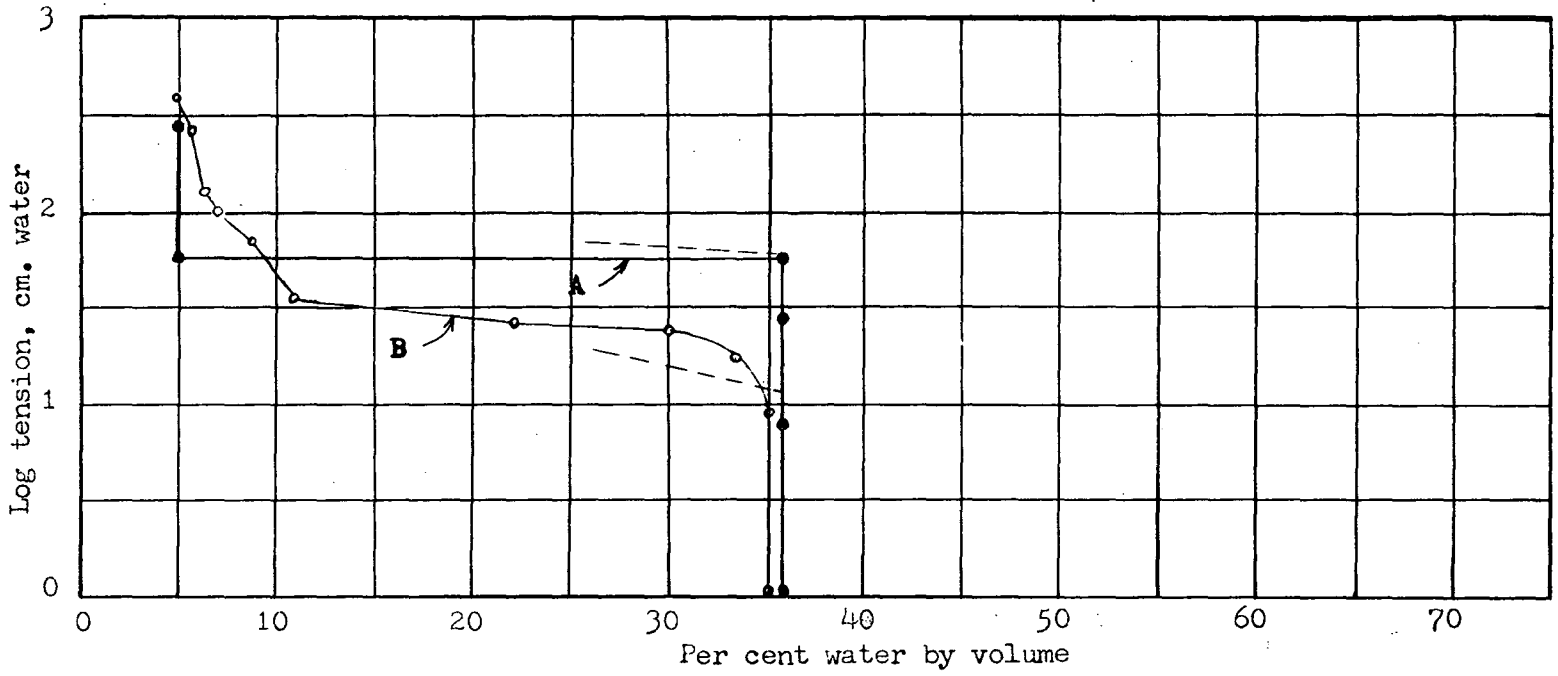


Fig. 5. The log-tension curves of mixed sand systems. A, 150 - to 270 - mesh over 40 - to 60 - mesh. B, 40 - to 60 - mesh over 150 - to 270 - mesh

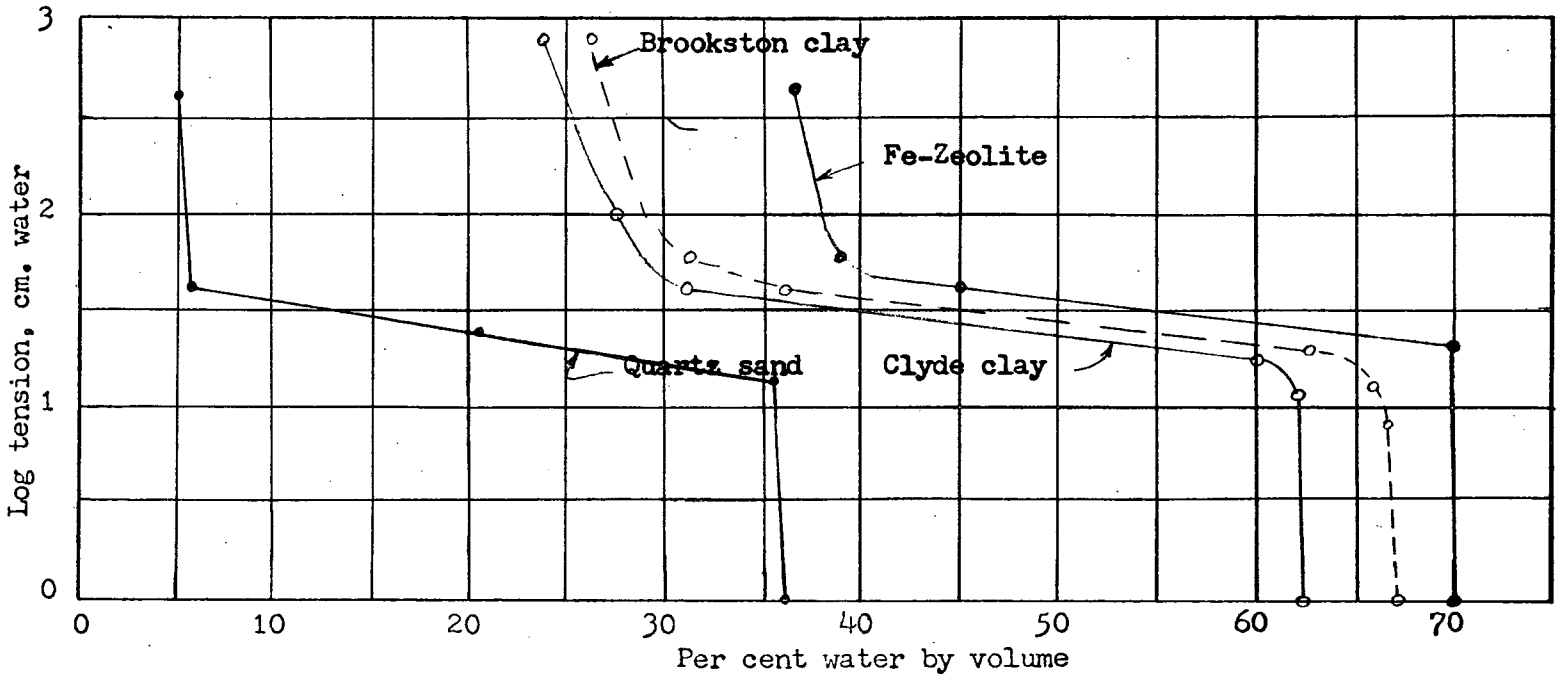


Fig. 6. Log-tension curves of 40 - to 60 - mesh systems of various materials

These curves show the effects of two carefully controlled sizes, and it is reasonable to expect that the pore sizes are also within a narrow range. In the "natural" soils used on this research, all minus 40 mesh with no lower limit, this would not generally be the case. Many factors are mentioned in the soil moisture literature as affecting moisture tension relationships. Nevertheless, it should be reasonable to expect that major factors influencing the type (shape) of curve obtained for each group are the pore sizes as determined by the gradation and the packing. The consistent mixing procedure should minimize differences due to packing; the groups should thus have curves that differ according to their gradation. The above seems to be verified by the gradations shown in Table 5 and the curves obtained (Figs. 7 through 22). Table 5 presents the analysis (percent gravel, sand, silt and clay) of each of the soils represented by the individual curves (Figs. 8, 10, 12, 14, 16, 18, 19, 20, 21, 22) which represent a "typical" clay, silty clay, silt, etc.

Referring again to Fig. 5, it is seen that a sample which depends essentially on one pore size reaches a point where it "unloads"; i.e., the holding capacity of every meniscus is reached at about the same tension and the pores are drained. This region may not be horizontal, (except in the hypothetical case where all the pores or pore necks are actually of the same diameter) but it is a definite region where slight increases in pressure cause relatively large changes in the moisture content of the sample. Consider another hypothetical case where the sample has its pore sizes more randomly distributed from smallest to largest. The curve of this latter "sample" should have a tendency to straighten; the sudden unloading effect would tend to be absent.

Table 5. Composition of soils used for individual curves plotted on graphs

Group	Designation number	Composition, percent gravel	sand	silt	clay
clay	508-4		12	42	46
clay	404-4		33	23	44
silty clay	45-1		1	66	33
silty clay	44-1		1	59	40
silty loam	AAD4-656	1	57	26	16
silty loam	AAD4-661	2	62	30	6
silty loam	AAD4-806	13	21	50	16
silty clay loam	AAD4-653	6	48	27	19
silty clay loam	70-1		7	70	23
clay loam	AAD4-664	1	41	38	20
loam	AAD4-647	3	43	35	19
silt	AAD3-12820			83	17
silt	AAD3-12822		3	90	7
silt	AAD3-12832		1	86	13
sand	AAD3-12829		90	8	2
sand	AAD4-828		89	10	1
sand	AAD4-3655		34	39	27
silty loam	I-2		1	81	18
gr. loamy sand	AAD4-809	14	71	11	4
sandy loam	AAD3-12807		63	24	13

In Fig. 6, Baver (7) presents log-tension curves of 4 different soils, all of controlled size (40 - to 60 - mesh except the Fe-zeolite which is 40 - to 80 - mesh). Because of their controlled size it is reasonable to expect the pore space between the aggregates does not vary greatly. To quote Baver (7):

> "These results indicate that the porosity of an aggregated system as determined by the amount of water withdrawn from the system from saturation up to the flex point on the log-tension curve, may be considered to be that between the aggregates. The water removed at the flex point may include some water at the contact points of the particles. The water drained out of the system just above the flex undoubtedly comes from the larger pores within the aggregates."

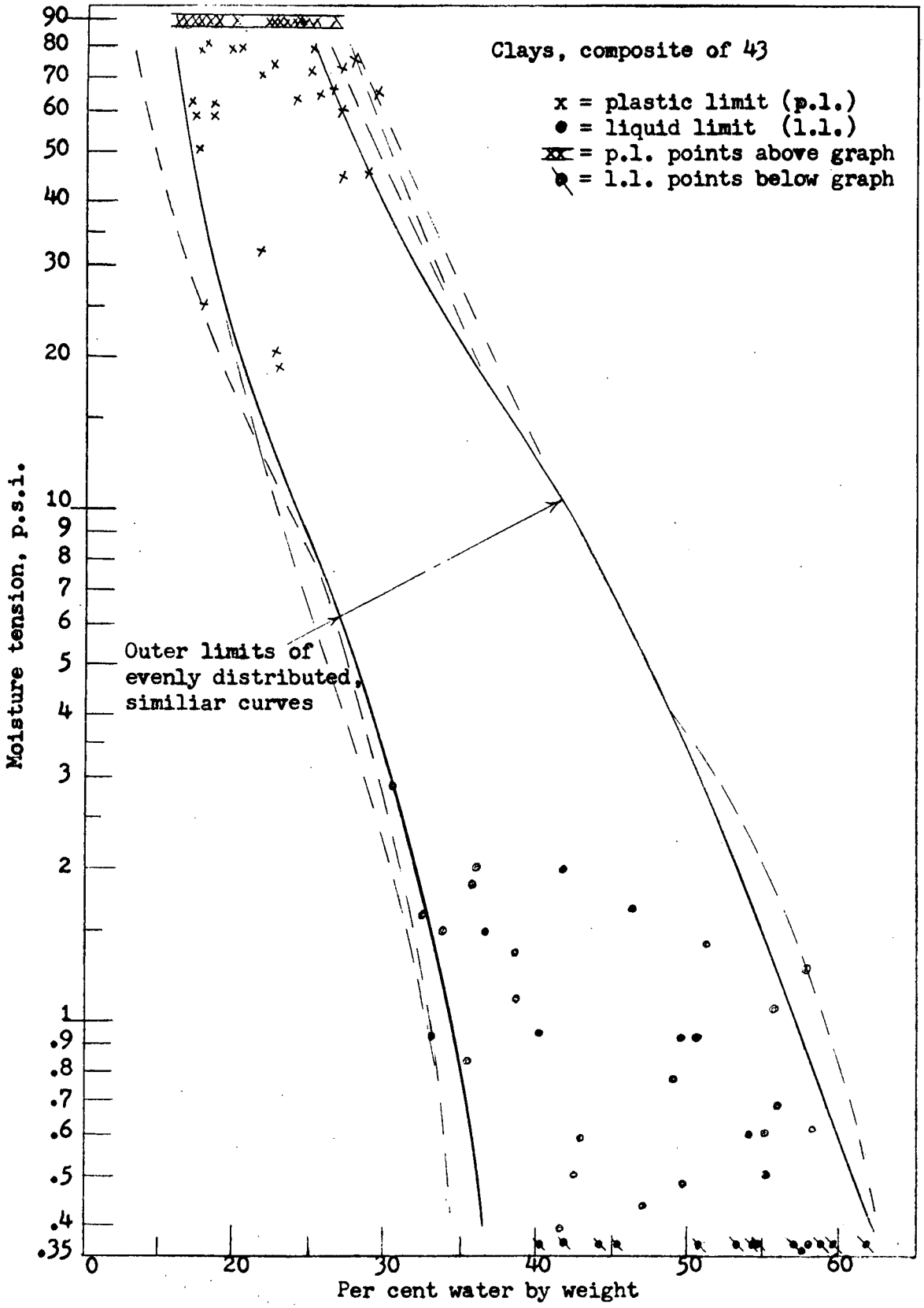


Fig. 7. Composite curve of 43 clays showing general distribution of the consistency limits

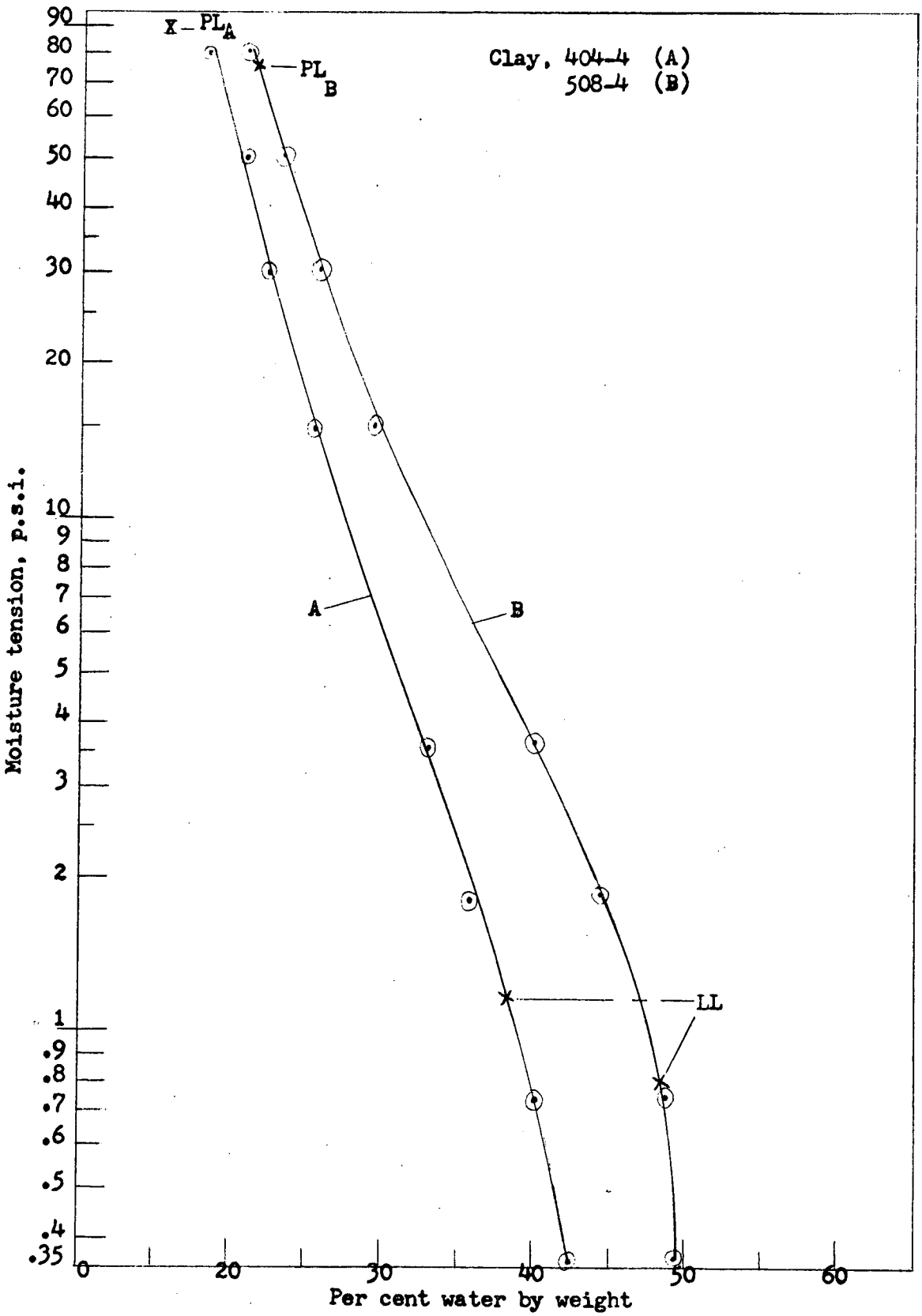


Fig. 8. Two clays typical of the group

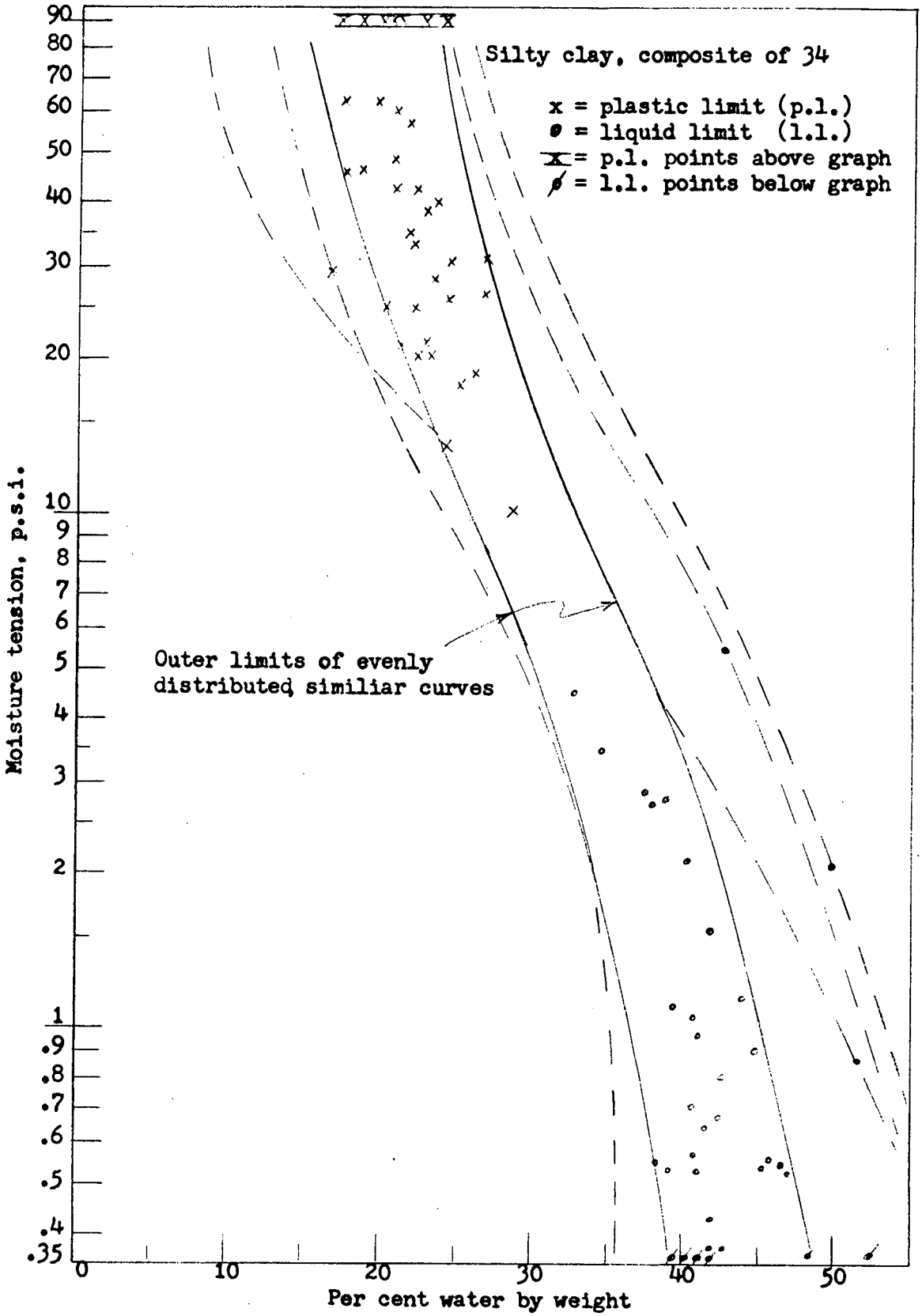


Fig. 9. Composite curve of 34 silty clays showing general distribution of the consistency limits

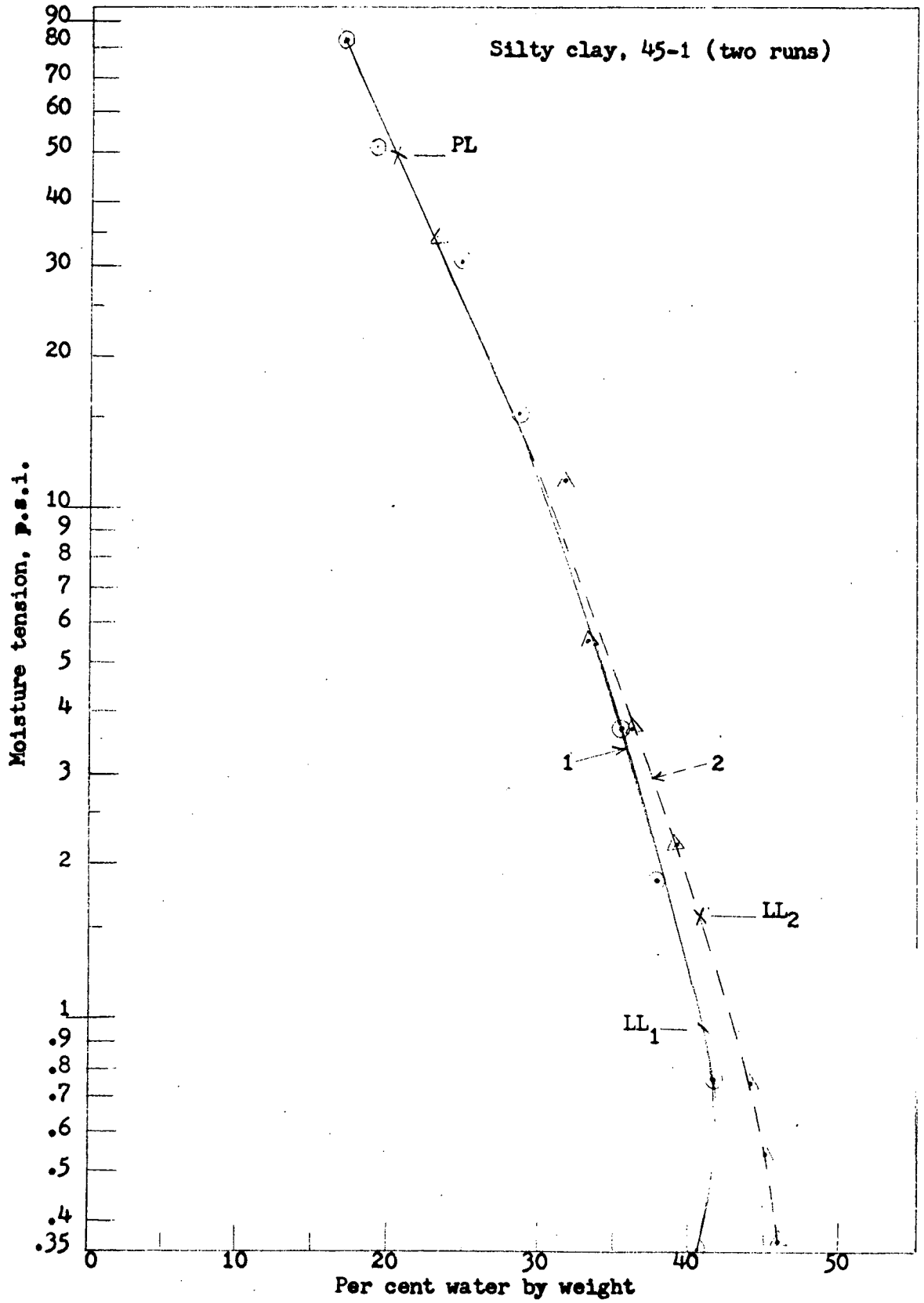


Fig. 10. Silty clay typical of the group

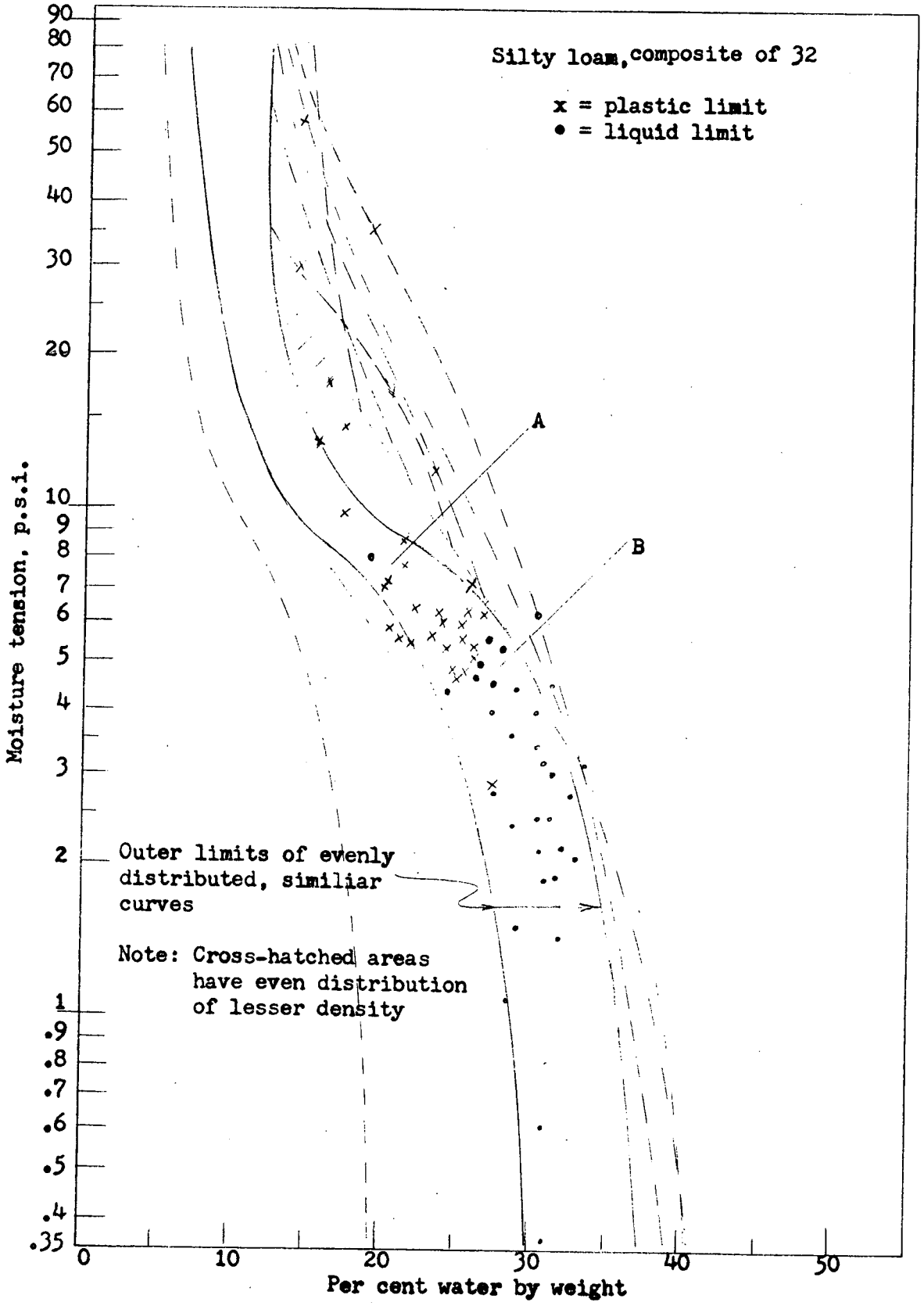


Fig. 11. Composite curve of 32 silty loams showing general distribution of the consistency limits

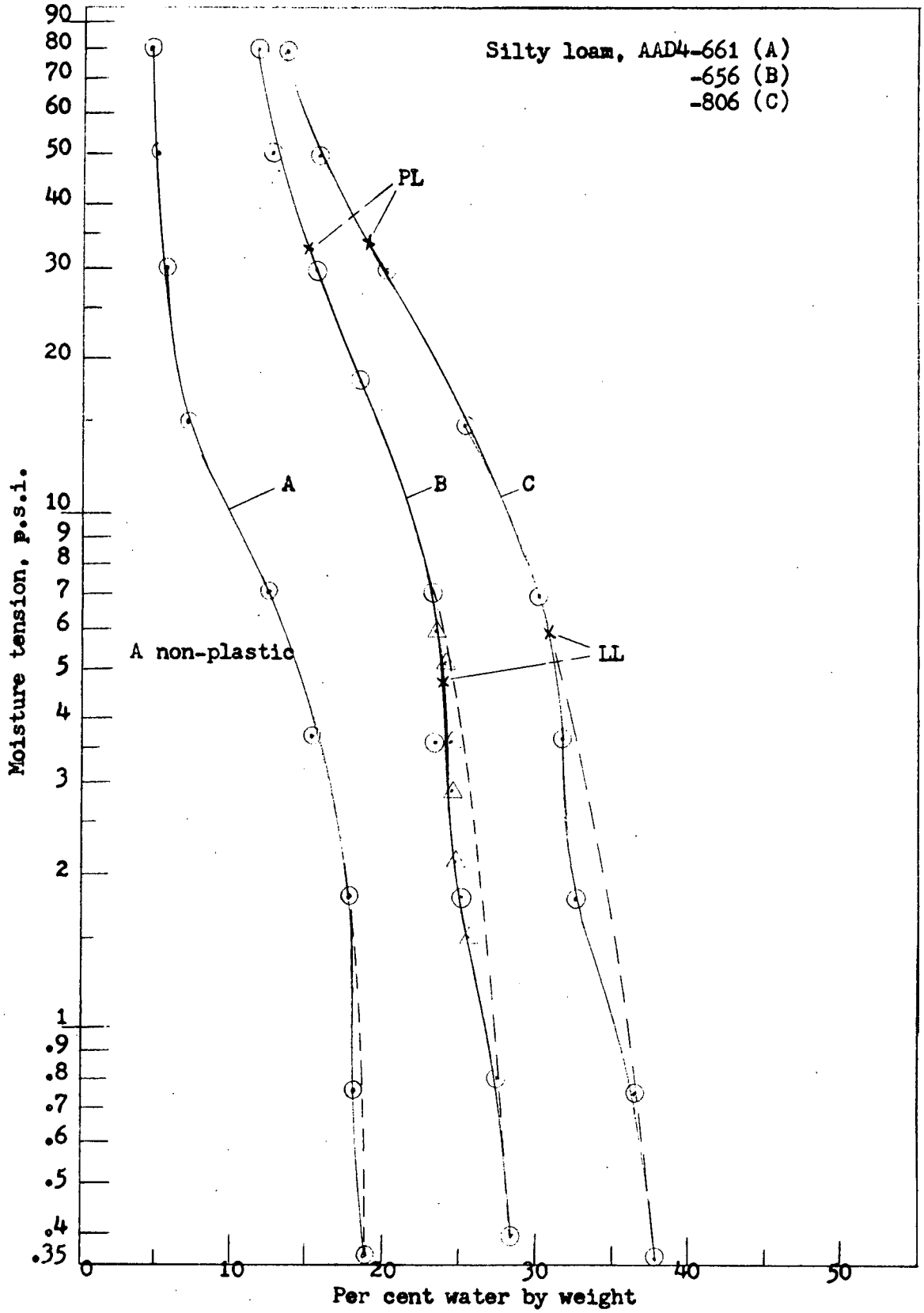


Fig. 12. Three silty loams typical of the group

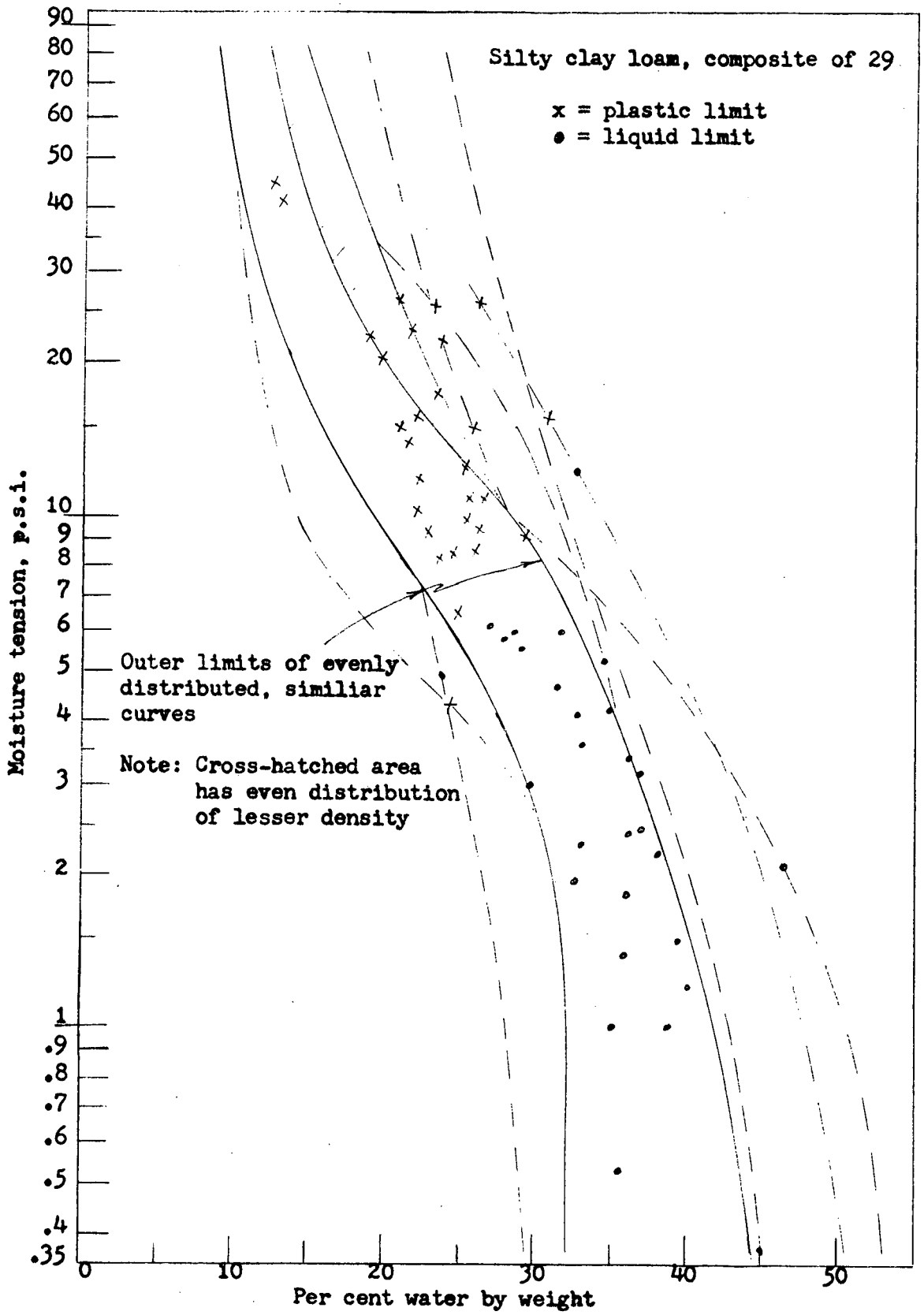


Fig. 13. Composite curve of 29 silty clay loams showing general distribution of the consistency limits

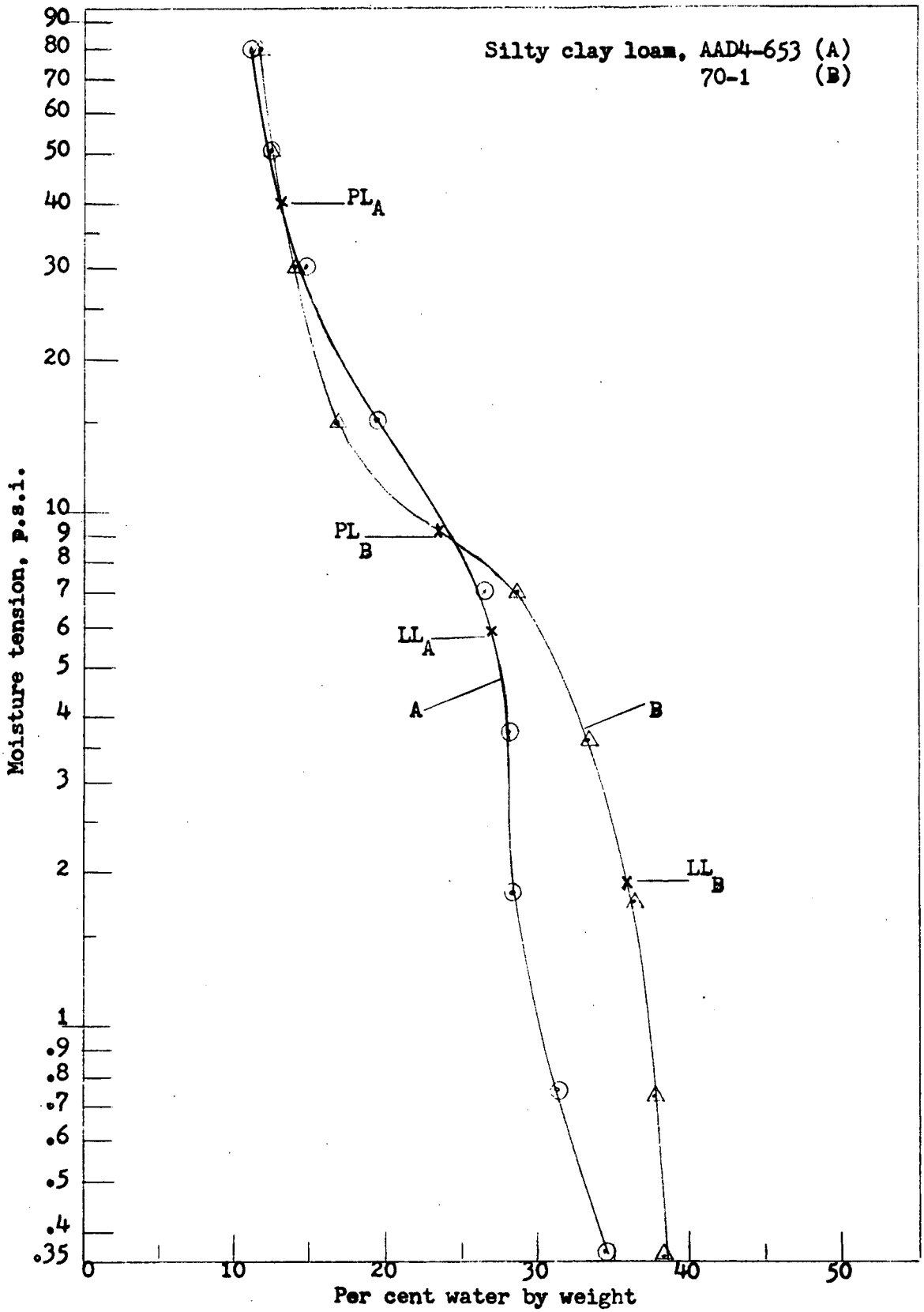


Fig. 14. Two silty clay loams typical of the group

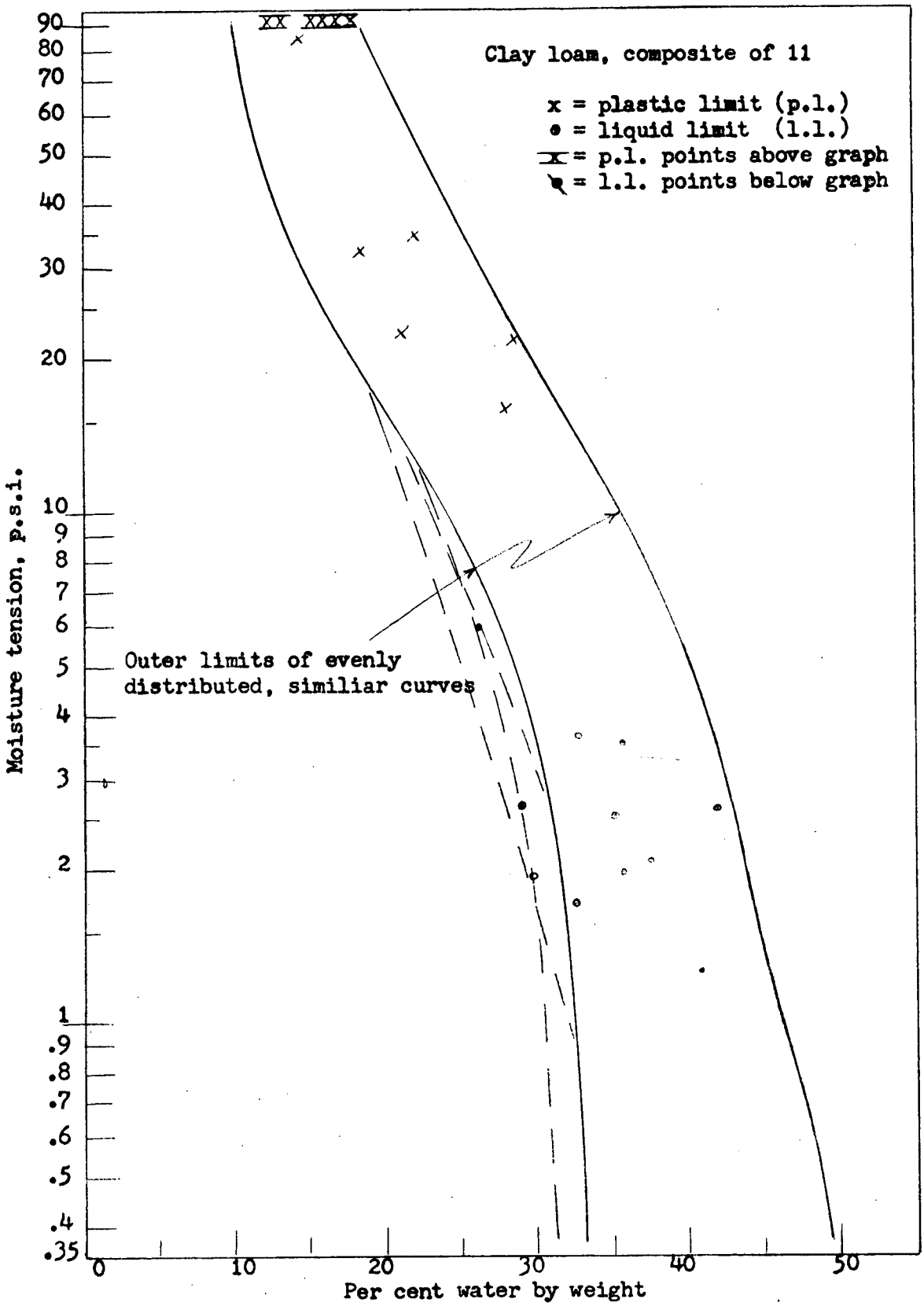


Fig. 15. Composite curve of 11 clay loams showing general distribution of the consistency limits

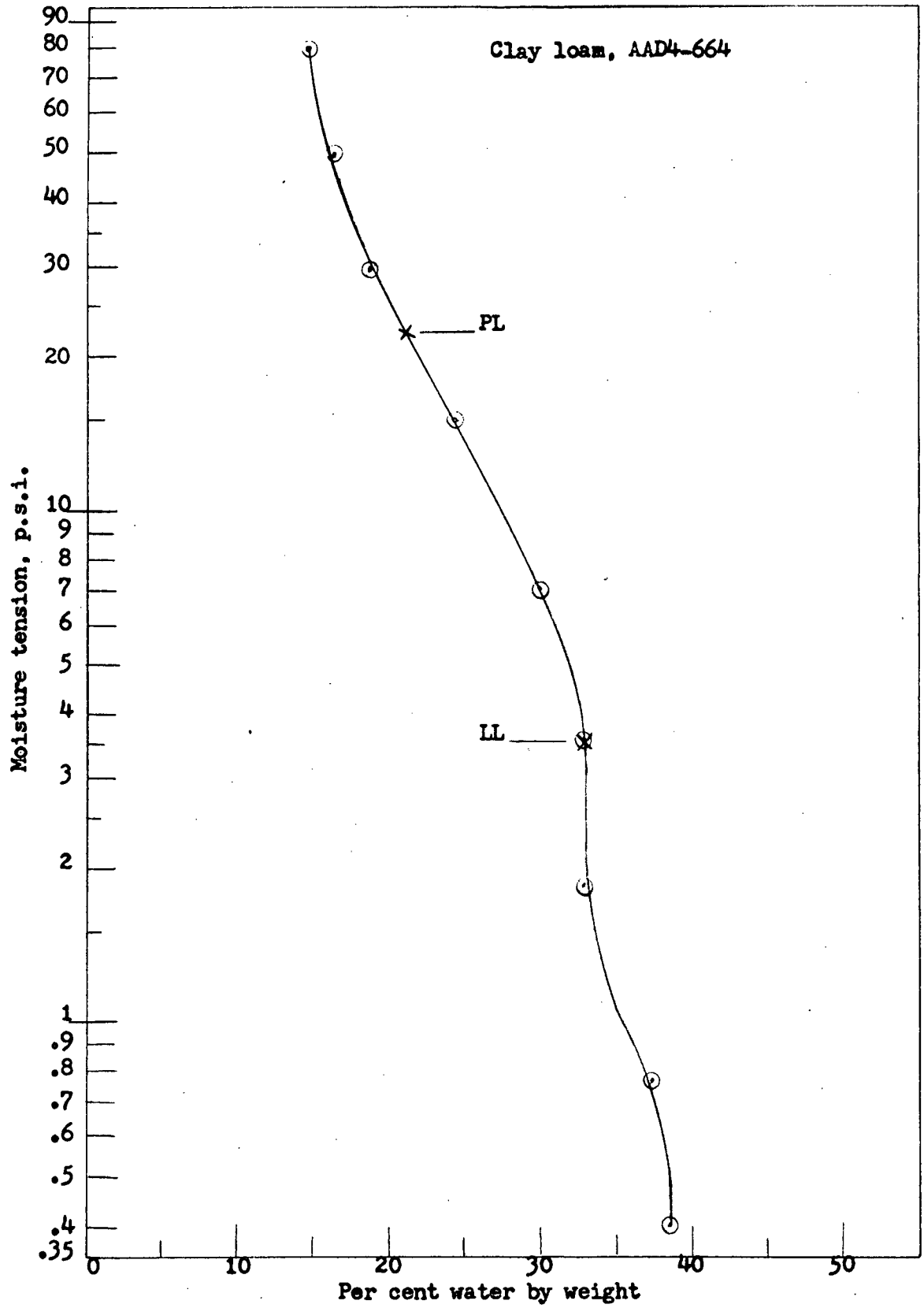


Fig. 16. A clay loam typical of the group

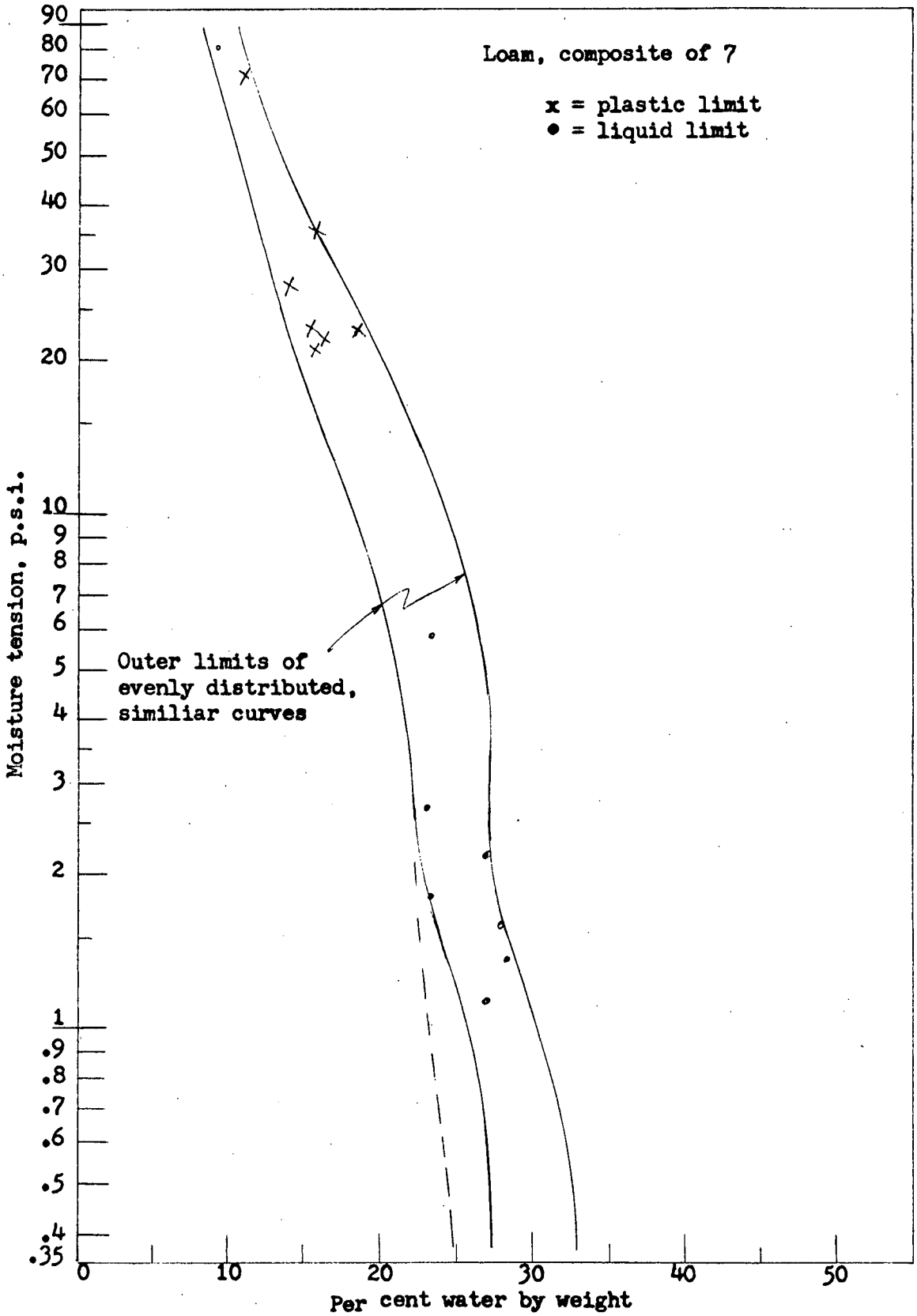


Fig. 17. Composite curve of 7 loams showing general distribution of the consistency limits

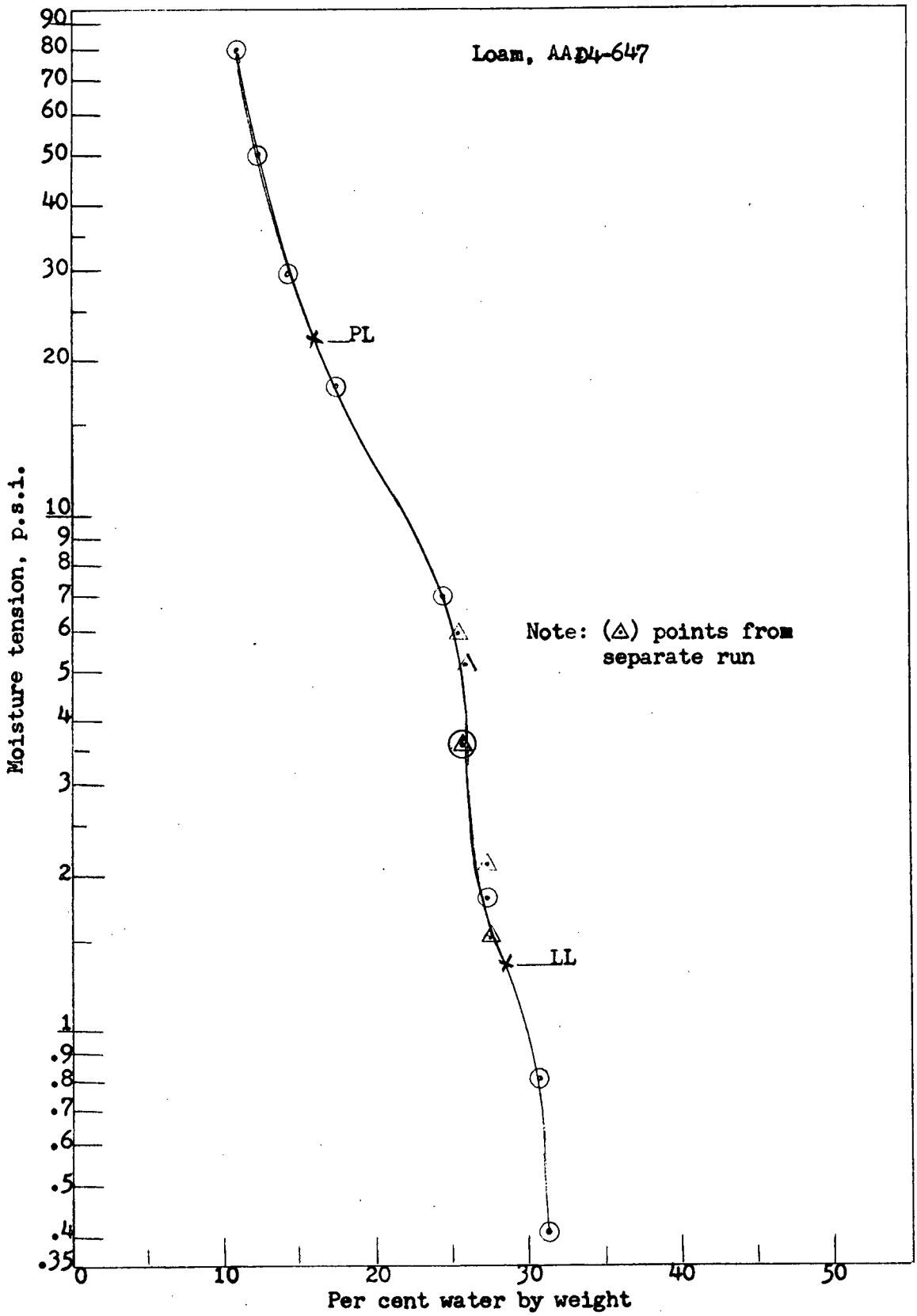


Fig. 18. A loam typical of the group

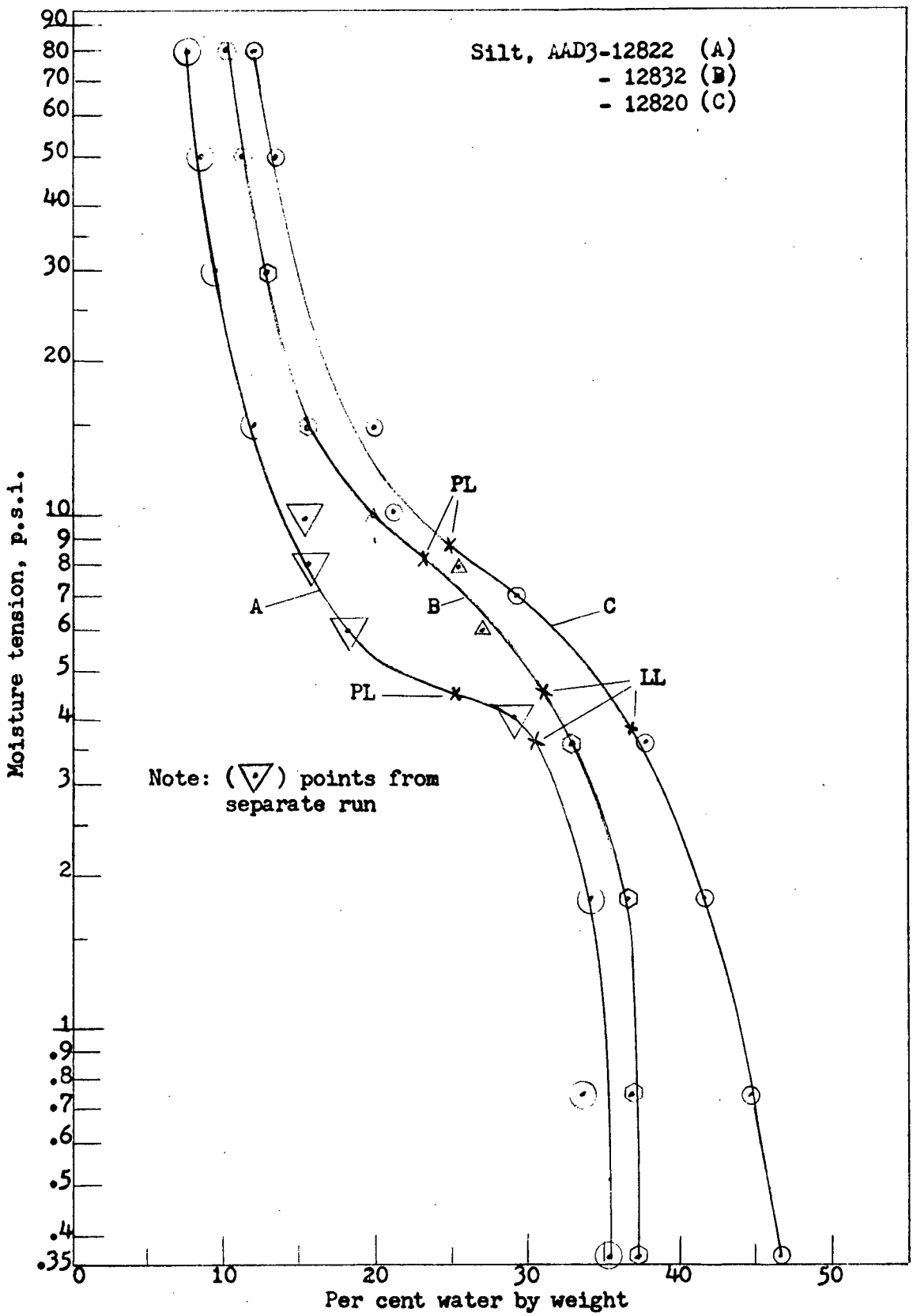


Fig. 19. Three silts representing the group

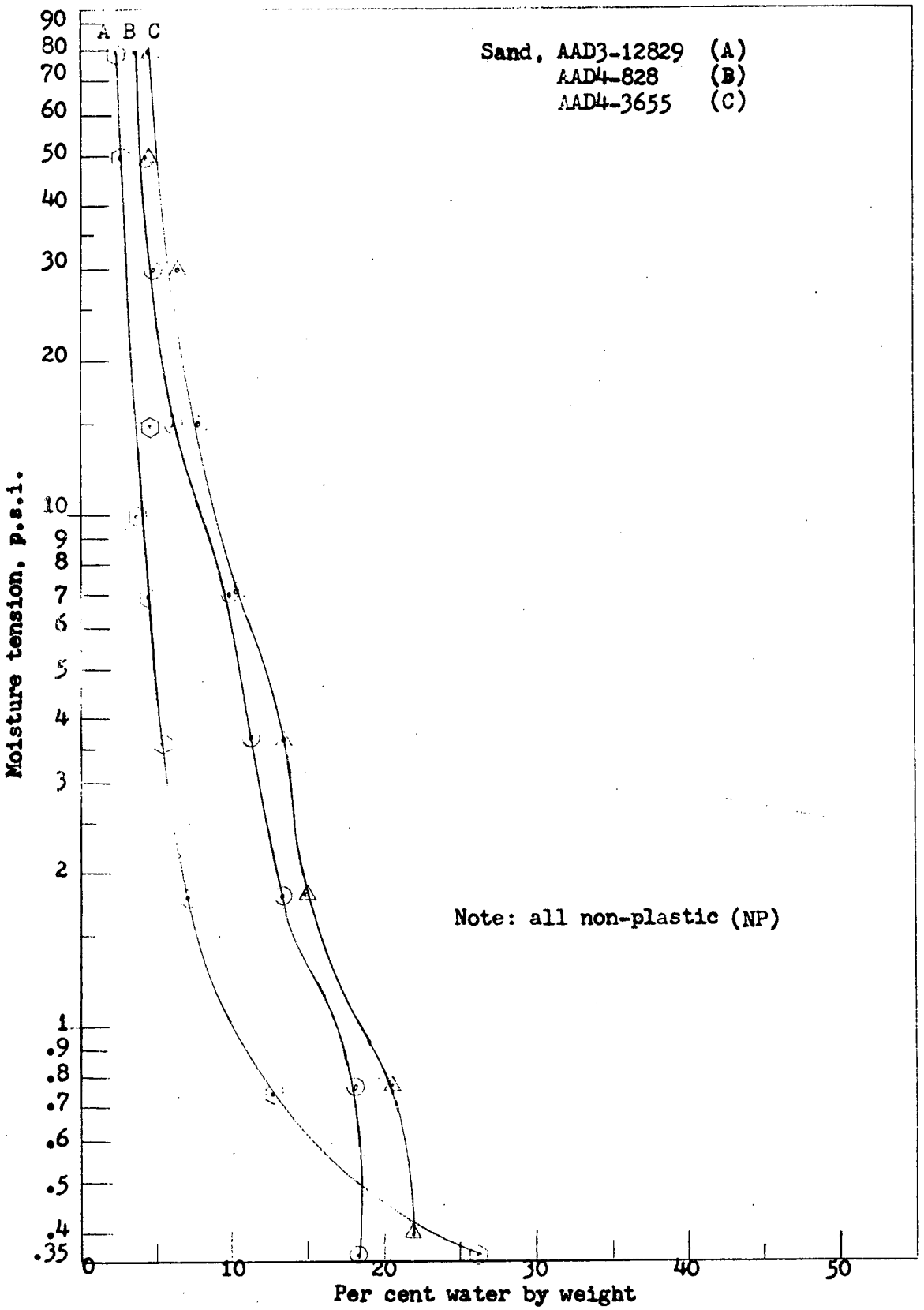


Fig. 20. Three sands representing the group

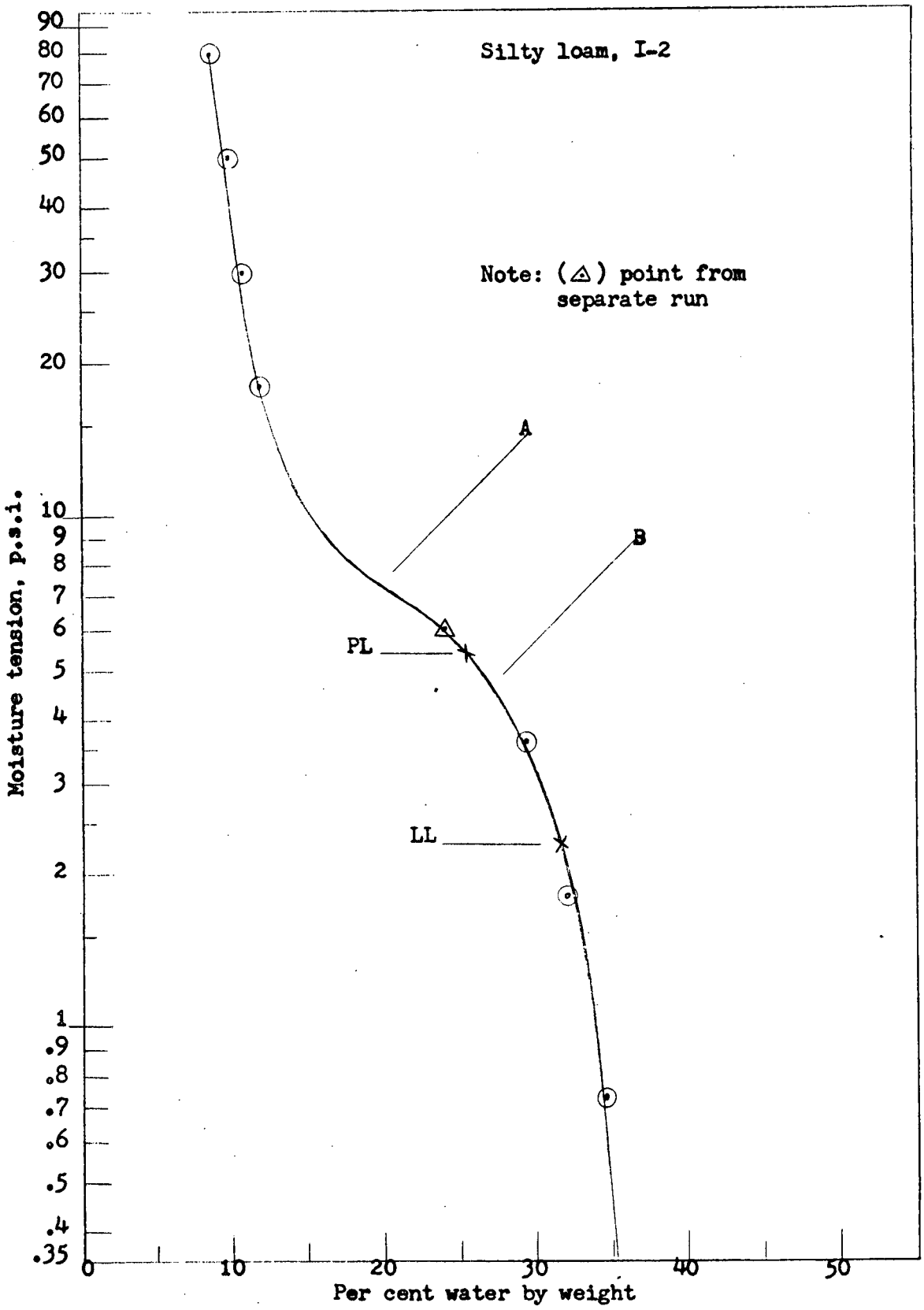


Fig. 21. A silty loam representing the group

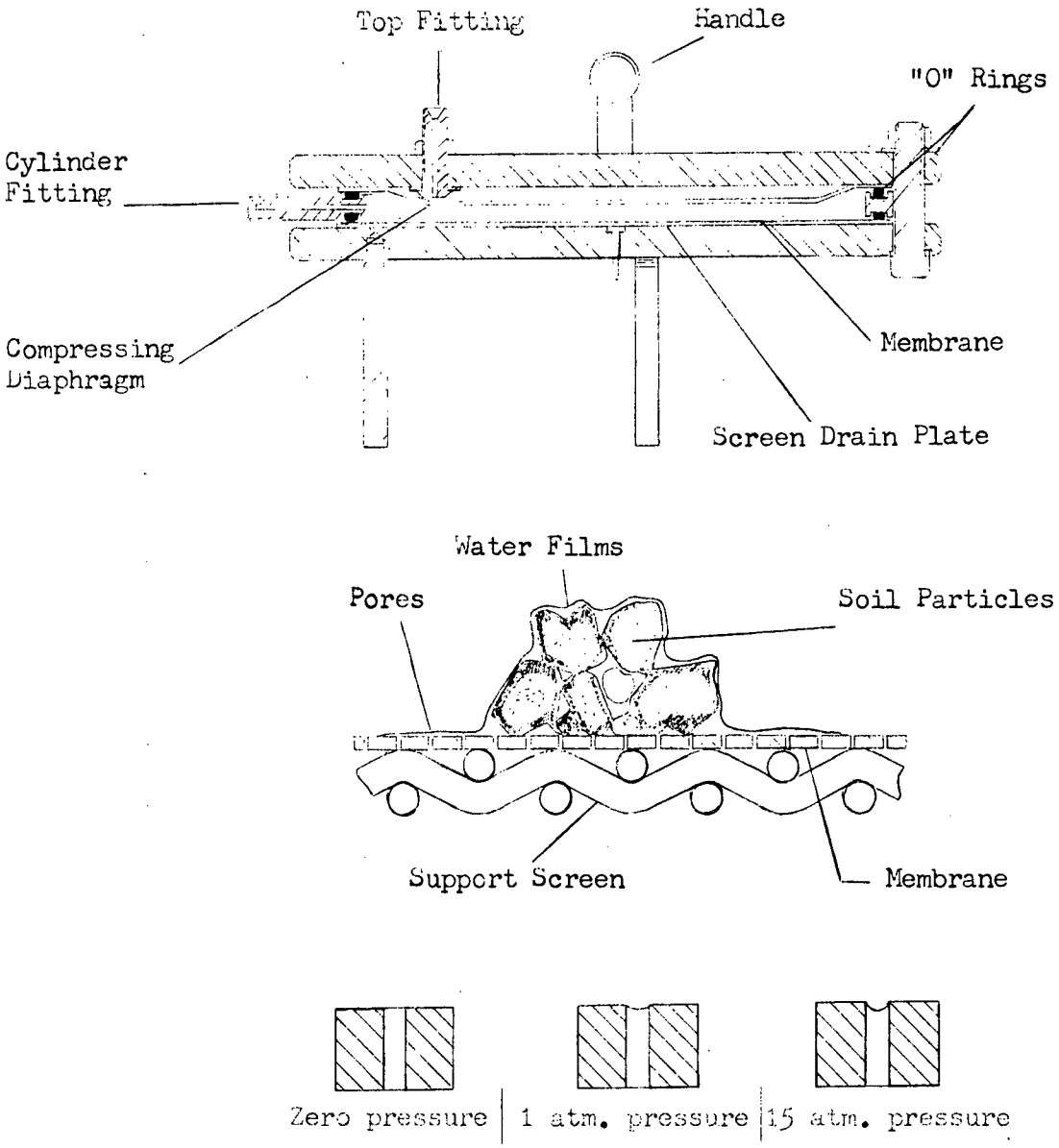


Fig. 4. Pressure membrane apparatus

Top: Cross-section

Center: Enlarged cross-section showing a soil sample during a run

Bottom: Enlarged cross-section of one pore of the membrane showing relative meniscus shape during three different pressures

Table 6. Comparison of the composition of clays from opposite extremities of the composite clay, Fig. 7.

a. Clays that plotted close to the left boundary					b. Clays that plotted close to the right boundary				
Soil number	Composition, percent gravel	sand	silt	clay(5μ)	Soil number	Composition, percent gravel	sand	silt	clay(5μ)
411-2	3.5	23.5	30.0	43.0	500-2	0.8	47.6		51.6
413-2	0.2	17.2	31.6	51.0	503-2	1.7	50.3		48.0
415-2	2.7	29.2	30.9	37.2	504-6	6.5	45.1		48.4
505-4		22.7	40.9	36.4	509-2	1.7	49.3		49.0
507-3		31.2	35.4	33.4	511-3	0.7	46.3		53.0

Baver does not discuss the upper portions of the curves. He does point out that water holding capacity is influenced by the clay content, the type of clay mineral, the amount of organic matter, and the amount of porosity of the aggregates. He also discusses the total potential of the soil water system, which gets into a thermodynamic discussion which is neither necessary nor desirable for the objectives herein.

It is reasonable to expect (although this is not said or inferred by Baver) that these other forces would mask the effect of capillary tension in the region of the upper flex. In other words, after the unloading region which represents water drained from the larger pores, the effect of pore size is no longer predominant. It should follow that, above this second flex, the sample has reached a state of "dryness" where forces, such as the attraction of oriented dipole water molecules on the surfaces of the particles, has a strong effect. Large pressure increases would be required to remove small amounts of the water that remains.

If all the above is valid, and if Grim's (22) theoretical definitions of plasticity and the consistency limits are also valid, then the definitions can be closely related to regions of the curve without excessive speculation. The portion of the moisture tension curve from saturation to the flex point, may be considered to be that between the aggregates and the water at the flex point may include some water at the contact points of the particles (7). Compare this statement above to Grim's (22) liquid limit definition:

> "---The liquid limit is a measure of the water which can be held with any substantial rigidity, and does not separate the particles, but approaches the point where there is substantially no bonding force between them.---"

This point represents the verge of separation; the flex point, coming from the "other direction" could be said to be just past the end of separation. It should be reasonable to assume that these points are analogous. Thus, the lower flex point of the moisture tension curve should represent the liquid limit.

The plastic limit is a measure of the water content just slightly in excess of the amount that a particle surface can adsorb in a highly rigid condition and which does not separate the particles enough to reduce attractive forces between them (22). In addition to the water between particles it is estimated that there is some pore water present (22). Considering the unloading region above the flex point of the moisture tension curve (7):

> "---The water drained out of the system just above the flex undoubtedly comes from the larger pores within the aggregates.",

it should be reasonable to assume that the point where the larger pores are drained suggests that the pore water left is not a simple function

of pore size. That is, the upper flex point, just below the region where it takes large increases in pressure to remove small amounts of water, should represent the plastic limit.

It follows that the unloading region between the upper and lower flex points of the curve would be the plasticity index. The plasticity index may be defined as the measure of the amount of water that can be added between particles, between the end point of rigid water and the point of particle separation, beyond which there is essentially no attractive force between them (22). Or, considering it analogous to the region above the lower flex of the moisture tension curve; it is the region where the water being drained out of the system comes from the larger pores within the aggregates. It follows that it is the range where the effect of pore size is predominant.

Using the above concepts of moisture tension curves as background, the following discussion will be of the curves obtained from data determined during the first phase of this project. The curves (Figs. 7 through 22) represent 167 different soils from 11 textural groups. The curves for six groups (clay-Fig. 7, silty clay-Fig. 9, silty loam-Fig. 11, silty clay loam-Fig. 13, clay loam-Fig. 15, and loam-Fig. 17) are shown as composite curves, showing limits between which most of the curves were evenly distributed. A trace of those curves that are definitely outside the general trend are shown as dotted lines.

Following each group is a graph of one or two curves from the group that appeared to be most typical of its group (Figs. 8, 10, 12, 14, 16, and 18). The remaining groups, silt (Fig. 19), sand (Fig. 20), silty loam (Fig. 21), sandy loam (Fig. 22 left) and gravelly loamy sand (Fig.

22 right) were presented in their entirety, because only the few shown were run.

Based on the validity of using textural groups to divide the samples (43), each group should have resulted in a family of curves within narrow limits. That this was not the case can be readily seen by the composite clay group (Fig. 7). This wide band is easily understood in relation to the common triangular textural chart which divides textural groups by their sand, silt, clay composition. The clay section of these charts is generally large and includes a wide range of varied composition. The difference in composition between curves near the right and left boundaries can also be seen from their composition as presented in Table 6. Those representing the left side of Fig. 7 are more well graded while those representing the right are almost entirely silt and clay.

If it were necessary to narrow the band, it would be necessary to find some other criteria besides textural groups. However, the final results seem to indicate that the group width is not of any great importance. With the common triangular chart in mind, it is easy to visualize that the width of all the bands presented is approximately proportional to the size of the group limits on the chart. That is, the larger the section on the chart, the greater the composition can vary.

Although their limits vary considerably, the curve shapes can be roughly related to the previous discussion of Baver's (7) curves if the following are kept in mind:

1. his material was limited to size between 40 and 60 mesh;
2. the scale of his curves (relative to the curves of this work) causes a horizontal "distortion"; and,

3. the abscissa of his curves represent percent water by volume which is more directly converted to porosity.

As can be seen in Table 5, and Figures 14, 19 and 21, the samples that perhaps come closest to having particle sizes equal or within relatively narrow limits, are the most obviously analogous to Figs. 5 and 6. That is, the three regions - relatively flat slope between two flex points - are easily discerned. It is also apparent from Fig. 14 which shows two silty clay loams of distinctively different shape, that composition (sand, silt, clay) affect the unloading region. It can be seen by the data of Table 5 that curve B is predominently silt (71%) while curve A is obviously more well graded.

The distinctive unloading region is also noticable to a lesser degree in the loam (Fig. 18), the sandy loam (Fig. 22 left) and the gravely loamy sand (Fig. 22 right), and to a minor degree in all curves.

The clays show the least curvature, and some (curve A, Fig. 8) plotted essentially as a straight line. This "straight line" could be due to greater pore size distribution and also, predominance of small pores and clay particles which cause forces other than meniscus tension to predominate. Most clays, however, showed at least a slight lower flex (curve B, Fig. 8) and, in some cases, curvature in the upper regions may have been more noticable at higher pressures.

In between the "straight" clay curve and the sharply curving silts are those with intermediate curvature; e.g., silty clay (Fig. 9), silty clay loam (Fig. 13) and clay loam (Fig. 15). Although data has not been analysed in such a way as to make quantitative conclusions, the sharpness of curvature could probably be related to the proportion of silt, relative

to the clay.

One of the sands (curve A, Fig. 20) appears to be distinctly different than the other two sands, and even from all other curves. However, its composition (Table 5) is distinctively different than the other two sands. It appears to be very well graded (sand-34%, silt-39%, clay-27%) and could have a system of pore sizes distributed in such a manner that it tends to start out as a straight line; or the character of the pores could be such that a lower flex would occur at a pressure below the curve range (0.35 psi). In other words, the lowest pressure is already in the unloading region.

One other distinctive occurence was noted. Some curves, notably the coarser soils such as the loams and sand, exhibited a "secondary lower flex." This lower curvature can be clearly seen in Fig. 12. At first it was thought that the points were in error and that the curves should follow the dotted lines. Several curves were rerun with points especially in this region (curve B, Fig. 12) and in every case this lower curvature was verified.

This effect appears to occur predominently in soils with a relatively high proportion of sand. Comparing the two curves of Fig. 14 with their composition in Table 6, it can be noted that curve A (which has the secondary lower flex) has 48 percent sand compared to 4 percent for curve B. The sand may create a relatively few pores or pockets, some with "weak" necks, so that a "minor unloading" begins that is not representative of the majority of the pores, after which the majority of the pores, that are more representative, are still saturated.

It has previously been suggested herein:

1. that the lower flex point could represent the liquid limit;
2. that the lower flex points should occur at about the same pressure; and,
3. the upper flex point could represent the plastic limit.

The results were too varied to give any concrete verification to these concepts. There were many exceptions. However, there is also a preponderance of data that suggests that it should not be ruled out. In the silty loam group for example, a large majority of the plastic limits occurred close to the point of tangency of the two curves (region A-B, Figs. 11 and 21). A similar concentration may be found on the silty clay loam composite (Fig. 13) and the loams (Fig. 17). Although single curves are scanty evidence, Figs. 16, 18, 19, 21, and 22, show a rather idealized picture.

The liquid limits appear to be extremely variable. In fact, picking a pressure from the wide scatter of points appeared to be impossible, and trial and error was finally resorted to. However, the steepness of the curve in this region of very low pressures means that large vertical deviations on the first cycle of the graph result in only small changes in moisture content.

Consider also that it is entirely arbitrary to discredit the curves and say a point is in "error" because it doesn't agree with the standard liquid limit to which it is compared. If the curve flex point were the "standard," a slight variation in the standard (ASTM) liquid limit would cause it to be far off the flex point and it could be said to be in "error."

The clays and silty clays show liquid limit points well below the

lower flex. In the clays, forces other than meniscus tension could contribute to this condition and result in raising the flex. On the other hand, perhaps the definition of plasticity based on particle separation and cohesive forces (22) should not be strictly applied to clays and coarser materials alike.

During the second phase when the curves were used to pick a pressure to approximate the liquid limit, pressures were picked off the curves at each consistency limit. An average was figured as a starting point. It was found to be only a rough approximation, and many trial and error adjustments were necessary. In retrospect, the average was probably not the best figure to use. There were apparently enough widely scattered values to make the average value of little practical use. The mode would probably have given a closer starting point, or a point picked visually from the center of a composite such as shown in the figures.

After several trials and adjustments, good liquid limit values were obtained at the pressures, given in Table 7.

Good results were obtained at pressures within a relatively more narrow range of pressures than the composite curves would indicate. However, they are in a cycle of the graph where the differences in pressure are "exaggerated". In other words, the points (dots of the composite figures) can vary relatively widely, vertically, with relatively small change in the corresponding pressure and moisture content. By entering all the composite curves with the final pressures, it can be seen that the point would fall essentially near the center of the scattered points. There is still the possibility that if all the soils were run at one pressure, 60 in. of water for example, the results would be acceptable.

Table 7. Summary of suitable pressures for approximating the liquid limit

Group	Final pressure (in. of H_2O)	Final pressure (p.s.i.)
clay	40	1.44
silty clay	40	1.44
silty clay loam	60	2.17
clay loam	60	2.17
loam	70	2.53
sandy loam	70	2.53
gr. sandy loam	70	2.53
silty loam	70	2.53
silt	70	2.53

The plastic limits required more adjusting trials than the liquid limits, the final pressures were more varied and the results achieved were not as good. This fact appears to be contrary to the closeness that the points showed on most of the composite curves. However, it must be kept in mind that they are in a region of the graph where small changes of pressure correspond to large changes in moisture content. Also, the plastic limit is less clearly defined by both the standard method and by its relation to the curve.

Plastic limit values were determined only for four groups. The final pressure values used are given in Table 8.

The second phase of this project consisted of running numerous samples at the final pressures indicated in Table 7 and 8.

The liquid limit results obtained for 687 soil samples from nine different textural groups and one "combined" group are presented in Tables 9 through 18. Data for an approximation of the reproducibility of liquid

Table 8. Summary of suitable pressures for approximating the plastic limit

Group	Final pressure (p.s.i.)
clay	162
silty clay	70
silty clay loam	35
clay loam	70

limit values by both the standard and moisture tension methods are presented in Tables 19 and 20 respectively.

The plastic limit results obtained for 273 soil samples from four different textural groups are presented in Tables 21 through 24. Data for an approximation of the reproducibility of plastic limit values by both the standard and moisture tension methods are shown in Tables 25 and 26 respectively.

A summary and evaluation table of all the liquid limit results is presented as Table 27, and Table 28 presents plastic limit results in the same manner.

Samples were run as they were obtained from the Iowa State Highway Commission, and this fact is the main reason for the great difference in the number of samples that were run from each group; e.g. 168 clays, but only 6 silts (5 of which were repeated). In other words, the number of samples received from the commission contained different textural groups roughly in proportion to their abundance in Iowa soils.

The number of samples run from the groups with a limited number of

Table 9. Moisture content for 40 in. H_2O moisture tension compared with the liquid limit of clay soils

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-6522	51.73	52.50	52	3	49	15	34	24	31	42
" 6523	40.49	40.34	40	1	39	13	26	38	26	34
" 6525	56.53	54.75	55	-4	59	21	38	12	34	54
" 6530	54.48	54.75	55	-1	56	19	37	7	44	49
" 6533	39.24	38.83	39	-1	40	13	27	30	33	35
" 6535	47.05	46.60	47	-2	49	19	30	23	32	44
" 6538	47.58	47.34	47	-2	49	23	26	23	31	45
" 6542	39.90	39.13	39	1	38	13	25	30	32	36
" 6545	53.90	54.16	54	-1	55	17	38	17	36	47
" 6550	62.32	63.36	63	-2	65	16	49	7	39	54
" 6553	44.55	43.73	44	-2	46	20	26	16	45	38
" 6554	40.30	40.20	40	1	39	12	27	30	34	35
" 6556	48.65	47.93	48	-2	50	22	28	14	43	43
" 6557	50.30	49.80	50	-4	54	19	35	21	30	48
" 6558	39.36	38.71	39	5	34	15	19	28	30	34
" 6566	39.90	39.91	40	3	37	15	22	19	43	36
" 6567	38.70	38.79	39	2	37	14	23	22	37	39
" 6571	36.40	36.75	37	3	34	16	18	25	43	30
" 6572	40.80	40.84	41	2	39	17	22	26	30	41

*In Tables 9 through 17 and 21 through 24 the following footnote symbols will be applicable.

[a]Numbered and grouped in order that they were run.

[b]By weight, sample split into 2 sections.

[c]Average, to nearest number.

[d]Deviation, moisture tension minus standard.

[e]Standard limits run by Iowa State Highway Commission (ISHC).

[f]From ISHC records, gravel not shown.

[g]Sand.

[h]Silt.

[i]Clay.

Table 9. (continued)

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-6575	38.66	39.17	39	2	37	16	21	24	45	31
" 6576	44.24	44.10	44	5	39	16	23	30	29	39
" 6577	44.40	44.70	45	3	42	13	29	32	29	32
" 6591	52.45	51.59	52	-3	55	21	34	9	44	47
" 6593	43.92	43.16	44	0	44	16	28	30	29	34
" 6594	42.73	42.21	42	1	41	18	23	32	33	32
" 6595	34.79	34.67	35	3	32	13	19	37	29	30
" 6596	44.99	45.55	44	1	43	17	26	13	31	52
" 6597	31.46	31.28	31	4	27	15	12	27	36	28
" 6598	36.04	36.19	36	2	34	14	20	35	29	35
" 6603	40.98	44.63	42	1	41	25	16	23	46	31
" 6607	39.90	39.90	40	3	37	27	10	26	42	32
" 6612	36.78	37.05	37	4	33	17	16	6	47	45
" 6675	37.39	37.60	37	3	34	15	19	19	41	36
" 6686	46.88	47.42	47	-2	49	15	34	21	32	45
" 6691	45.30	47.67	46	0	46	14	32	20	34	43
" 6700	36.57	36.28	36	2	34	14	20	34	34	30
" 6744	69.46	71.00	71	0	71	21	50	0	31	69
" 6745	50.56	51.32	51	0	51	19	32	2	50	48
" 6746	68.54	68.60	69	-4	73	22	51	1	29	70
" 6534	44.12	42.91	43	2	41	25	16	24	44	32
" 6581	44.59	45.13	45	-1	46	14	32	19	37	43
" 6879	44.75	44.70	45	-4	49	20	29	7	25	65
" 6884	33.24	32.77	33	-2	35	14	21	36	31	30
" 6895	33.20	32.15	32	-1	33	14	19	32	36	32
" 6900	50.49	49.90	50	-1	51	20	31	8	28	59
" 6910	36.03	36.01	36	2	34	14	20	29	35	33
" 6920	35.33	33.79	34	1	33	15	18	35	27	36
" 6927	34.51	34.43	34	1	33	16	17	29	37	31
" 6940	33.12	32.68	33	0	33	14	19	32	33	30
" 6943	43.97	43.66	44	3	41	21	20	18	46	36
" 6944	46.72	47.23	47	-1	48	17	31	33	31	34
" 6963	44.17	44.62	44	4	40	17	23	33	27	40
" 6964	43.52	43.68	44	5	39	19	20	5	33	62
" 6965	44.64	45.18	45	6	39	18	21	5	31	63
" 6969	39.30	38.51	39	6	33	15	18	38	29	30
" 6970	33.39	33.40	33	2	31	17	14	16	43	38
" 6971	36.82	37.43	37	2	35	16	19	15	35	50
" 6972	41.19	40.74	41	-1	42	16	26	33	35	30

Table 9. (continued)

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-7014	40.40	41.12	41	5	36	17	19	37	27	33
" 7016	46.75	44.98	45	4	41	22	19	11	39	49
" 7018	30.42	30.31	30	-2	32	16	16	27	41	32
" 7026	36.36	37.02	37	-1	38	23	15	21	42	37
" 7030	42.16	42.39	42	-4	46	20	26	25	36	31
" 7031	48.82	48.47	49	-3	52	18	34	20	38	41
" 7032	49.74	50.30	50	-1	51	21	30	8	46	46
" 7036	40.69	40.62	41	-3	44	22	22	32	30	31
" 7037	40.91	42.01	41	-3	44	19	25	14	49	37
" 7107	30.79	30.90	31	0	31	13	18	35	29	30
" 7113	31.42	31.08	31	0	31	13	18	28	36	33
" 7171	58.26	57.92	58	-8	66	27	39	1	17	80
" 6581[k]	46.53	46.32	46	-0	46	14	32	19	37	43
" 6879[k]	45.54	44.79	45	5	40	20	29	7	25	65
" 6884[k]	32.77	32.57	33	-2	35	14	21	36	31	30
" 6895[k]	33.44	33.73	34	1	33	14	19	32	36	32
" 6900[k]	49.71	49.46	50	-1	51	20	31	8	28	59
" 6910[k]	34.52	34.81	35	1	34	14	20	29	35	33
" 6920[k]	33.30	33.72	33	0	33	15	18	35	27	36
" 6927[k]	33.87	33.78	34	1	33	16	17	29	37	31
" 6940[k]	31.95	31.22	32	-1	33	14	19	32	33	30
" 6943[k]	43.49	42.96	43	2	41	21	20	18	46	36
" 6944[k]	46.40	47.40	47	-1	48	17	31	33	31	34
" 6963[k]	46.07	46.05	46	6	40	17	23	33	27	40
" 6964[k]	45.44	45.69	45	6	39	19	20	5	33	62
" 6965[k]	47.14	46.72	47	8	39	18	21	5	31	63
" 6969[k]	38.13	38.41	38	5	33	15	18	38	29	30
" 6970[k]	34.60	34.54	34	3	31	17	14	16	43	38
" 6971[k]	37.86	38.84	38	3	35	16	19	15	35	50
" 6972[k]	41.31	41.11	41	-1	42	16	26	33	35	30
" 7214	54.22	54.22	53	-3	56	29	27	13	49	38
" 8162	46.36	45.23	46	2	44	25	19	11	49	40
" 8177	47.23	50.99	49	4	45	19	26	12	21	63
" 8179	57.01	56.66	57	2	55	21	34	3	23	74
" 8180	46.70	46.67	47	7	40	26	14	19	45	35
" 8187	40.87	41.52	41	3	38	18	20	9	48	43
" 8209	60.54	60.34	60	5	55	28	27	12	47	41
" 8228	37.75	38.05	38	2	36	16	20	14	50	36

[k]Rerun of samples above at a later date.

Table 9. (continued)

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-8239	41.40	40.96	41	2	39	20	19	21	49	30
" 9348	34.34	34.47	34	1	33	14	19	36	32	30
" 8265	57.39	57.19	57	-3	60	19	41	3	49	48
" 8266	52.34	52.06	52	0	52	16	36	10	48	42
" 8281	36.87	36.98	37	-2	39	16	23	37	28	34
" 8285	35.93	35.80	36	2	34	15	19	31	37	31
" 8294	35.27	34.65	35	2	33	15	18	31	32	35
" 8315	42.09	42.48	42	0	42	19	23	24	40	35
" 8326	35.12	34.91	35	1	34	15	19	22	48	30
" 8337	44.61	44.06	44	0	44	17	28	20	48	32
" 8342	37.16	37.34	37	-2	39	14	25	34	34	31
" 8347	41.01	40.93	41	2	39	18	21	21	40	38
" 8402	39.10	39.58	39	-1	40	21	19	19	50	31
" 8415	42.01	41.37	42	3	39	22	17	19	50	31
" 8416	48.28	48.27	48	-3	51	22	29	9	46	45
" 8423	37.31	37.44	37	-2	39	17	22	38	30	31
" 8428	35.98	35.47	36	-1	37	16	21	33	30	35
" 8438	36.79	36.36	37	0	37	14	23	25	44	31
" 8443	32.53	32.55	33	1	32	15	17	31	37	30
" 8444	40.75	40.56	41	-1	42	15	27	28	35	36
" 8447	62.24	62.18	62	-3	65	23	42	3	43	54
" 8458	50.62	50.54	51	-3	54	20	34	4	49	47
" 8461	50.14	50.04	50	2	48	28	20	16	46	38
" 8463	40.90	41.96	41	3	38	18	20	33	33	31
" 8465	40.48	40.22	40	2	38	20	18	21	44	33
" 8472	45.93	45.43	46	-2	48	23	25	12	49	38
" 8478	42.50	42.38	42	-2	44	19	25	21	45	31
" 8489	49.96	49.87	50	0	50	19	31	13	46	40
" 8491	56.67	57.46	57	-1	58	30	28	20	40	38
" 8492	55.24	54.63	55	-3	58	23	35	26	33	38
" 8493	61.88	61.68	62	0	62	26	36	2	44	54
" 9017	35.25	35.06	35	1	34	14	20	35	29	30
" 9018	56.43	55.90	56	0	56	32	24	30	34	34
" 9019	48.22	47.77	48	3	45	20	25	28	33	38
" 9036	32.81	32.66	33	2	31	16	15	40	25	32
" 9041	35.62	36.04	36	3	33	15	18	27	41	30
" 9055	37.33	36.85	37	1	36	16	20	36	34	30

Table 9. (continued)

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sag	si[h]	c[i]
AAD4-9036	42.97	43.38	43	2	41	19	22	11	49	36
" 9065	41.40	41.26	41	2	39	18	21	20	50	30
" 9067	57.81	57.19	58	-2	60	21	39	27	32	41
" 9068	37.92	37.41	38	3	35	16	19	28	37	34
" 9069	49.92	50.30	50	0	50	21	29	3	49	48
" 9076	60.53	61.22	61	-6	67	20	47	8	40	52
" 9084	57.83	57.98	58	-2	60	27	33	35	9	55
" 9091	41.60	41.84	42	-1	43	22	21	15	48	37
" 9094	39.09	39.03	39	-1	40	21	19	19	47	34
" 9095	86.25	86.54	86	-6	92	28	64	5	17	78
" 9097	82.77	81.66	82	-3	85	35	50	7	5	87
" 9101	40.80	40.55	41	3	38	22	16	20	49	31
" 9102	27.71	27.83	28	-8	36	20	16	20	49	31
" 9105	35.61	35.21	35	1	34	20	14	22	45	32
" 9116	51.69	51.30	51	1	50	22	28	6	32	62
" 9120	68.28	68.83	69	-8	77	31	46	11	15	74
" 9125	52.41	51.96	52	-2	54	34	20	15	45	40
" 9142	66.23	65.49	66	-10	76	29	47	9	22	69
" 9143	70.85	71.55	71	-9	80	29	51	0	19	81
" 9144	73.63	72.67	73	-7	80	27	53	0	25	75
" 9145	75.64	75.30	75	-7	82	28	54	23	38	35
" 9190	47.33	44.86	46	-1	47	18	29	23	38	35
" 9196	49.32	49.96	50	-1	51	17	34	19	37	43
" 9199	40.95	42.82	42	0	42	23	19	28	38	34
" 9203	51.64	52.58	52	-1	53	19	34	18	38	43
" 9215	42.88	42.88	43	-1	44	18	26	17	41	42
" 9216	38.38	38.31	38	-2	40	19	21	18	50	32
" 9220	40.02	41.25	41	6	35	19	16	9	39	43
" 9228	37.59	37.15	37	-1	38	19	19	18	49	32
" 9231	64.83	65.56	65	6	59	26	33	4	22	74
" 9286	54.62	53.76	54	-1	55	25	30	3	64	33
" 9282	39.30	39.22	39	-1	40	19	21	30	36	29
" 9310	45.48	45.43	45	1	44	16	28	19	42	36
" 9321	35.51	35.51	36	4	32	15	17	31	37	31
" 9347	47.08	46.86	47	-2	49	19	30	18	44	37

Table 10. Moisture content for 40 in. H_2O moisture tension compared with the liquid limit of silty clay soils.

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-3913	50.33	49.85	50	5	45	24	21	11	54	35
" 3917	39.56	40.28	40	3	37	18	19	4	58	38
" 3939	41.24	41.90	42	0	42	25	17	1	69	30
" 3946	44.14	43.26	44	3	41	22	19	2	64	34
" 3952	42.73	43.81	43	-1	44	21	23	12	57	31
" 6519	52.24	51.74	52	-1	53	27	26	3	51	46
" 6527	48.10	50.47	49	0	49	26	23	2	59	39
" 6528	43.50	42.81	43	-2	45	19	26	3	59	38
" 6529	40.80	40.97	41	0	41	16	25	7	54	39
" 6544	50.27	49.86	50	-3	53	21	32	3	53	44
"" 6548	43.90	43.91	44	-1	45	24	21	2	60	38
" 6549	47.96	48.44	48	-4	52	20	32	3	51	46
" 6551	44.91	45.09	45	-1	46	29	17	13	53	34
" 6552	45.68	45.83	46	0	46	24	22	7	51	42
" 6555	48.13	48.14	48	-1	49	25	24	11	53	36
" 6559	41.14	41.37	41	0	41	22	19	1	64	35
" 6569	31.89	31.83	32	1	31	20	11	8	73	19
" 6579	40.02	40.30	40	4	36	18	18	5	60	35
" 6580	38.18	38.00	38	2	36	14	22	16	52	31
" 6584	41.88	42.69	42	1	41	16	24	6	58	36
" 6585	40.90	41.14	41	1	40	25	15	1	67	32
" 6586	38.85	39.53	39	1	38	21	17	1	67	32
" 6602	44.79	44.95	45	-4	49	22	27	1	69	39
" 6605	35.02	34.61	35	2	33	16	17	24	46	28
" 6609	38.54	38.79	39	-1	40	19	21	1	68	31
" 6611	40.90	41.49	41	5	36	23	13	1	61	38
" 6613	37.73	38.03	38	0	38	20	18	1	68	31
" 6616	40.18	40.45	40	0	40	25	15	1	65	34
" 6617	42.64	42.51	43	2	41	31	10	1	67	32
" 6620	40.93	40.25	41	2	39	21	18	2	68	30
" 6650	40.28	40.37	40	1	39	24	15	1	58	41
" 6651	39.60	39.54	40	0	40	25	15	1	67	32
" 6652	38.74	39.09	39	0	39	22	17	1	66	33
" 6653	37.86	37.23	38	-4	42	21	21	0	68	32
" 6654	43.50	43.62	44	-2	42	24	18	0	68	32
" 6655	38.78	38.86	39	-1	40	24	16	0	66	34
" 6656	39.66	39.52	40	-2	42	24	17	1	69	30
" 6658	32.69	32.69	33	4	29	16	13	3	56	41

Table 10. (continued)

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-6659	39.74	40.20	40	-3	43	23	20	0	68	32
" 6660	35.06	35.18	35	1	34	22	12	1	67	32
" 3492	49.44	49.73	50	2	48	20	28	8	52	40
" 3494	46.04	46.40	46	1	45	26	19	1	65	34
" 3495	44.84	45.18	45	-4	49	24	25	1	59	40
" 3497	44.08	44.09	44	-2	46	19	27	1	57	42
" 3498	44.10	44.62	44	-5	49	21	28	8	53	38
" 3499	49.34	49.59	49	-6	55	21	34	0	58	42
" 3501	45.08	46.01	46	-2	48	22	26	10	51	36
" 3502	50.50	50.86	51	-3	54	21	33	0	56	44
" 3503	44.27	43.03	44	0	44	21	23	0	64	36
" 3504	47.51	47.44	47	-1	48	22	26	1	58	41
" 3520	48.04	47.51	48	3	45	28	17	0	62	38
" 3521	46.36	45.63	46	1	45	22	23	0	58	42
" 3522	42.22	41.17	42	0	42	23	19	0	56	44
" 3523	43.51	43.26	43	3	40	20	20	0	67	33
" 3524	45.20	49.14	45	3	42	21	21	0	64	36
" 3526	45.98	46.12	46	-2	48	26	22	0	57	43
" 3582	37.63	37.65	38	2	36	20	16	14	52	32
" 3631	39.95	39.88	40	1	39	17	22	2	68	30
" 3636	41.42	41.89	42	1	41	23	18	0	70	30
" 3639	41.12	40.54	41	1	40	21	19	0	68	32
" 3643	44.96	44.50	45	3	42	26	16	6	62	32
" 3675	45.98	45.89	46	-5	51	24	27	1	55	44
" 3676	46.57	46.57	47	-3	50	22	28	0	60	40
" 3677	41.38	40.53	41	-2	43	18	25	1	63	36
" 3681	35.41	34.88	35	1	34	21	13	1	67	32
" 3683	44.87	44.51	45	-3	48	18	30	0	62	38
" 3688	46.23	46.08	46	-2	48	26	22	0	62	38
" 3691	48.73	49.18	49	-3	52	24	28	0	56	44
" 3699	47.98	48.20	48	-4	52	22	30	1	57	42
" 3700	51.17	51.27	51	0	51	24	27	1	59	40
" 3702	53.19	51.92	52	-1	53	25	28	0	54	46
" 3703	45.15	44.29	45	2	43	19	24	2	60	38
" 3704	51.18	50.19	51	-9	60	25	35	1	51	48
" 3705	45.36	45.39	45	3	42	20	22	0	64	36
" 3709	45.83	46.33	46	3	43	25	18	1	61	38
" 3711	47.89	47.92	48	6	42	25	17	2	61	37

Table 10. (continued)

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-3712	47.35	46.32	47	2	45	25	20	1	62	36
" 3715	52.11	52.43	52	-1	53	25	28	0	56	44
" 3718	54.20	54.10	54	-1	55	22	33	0	52	48
" 3735	41.96	40.40	41	2	39	20	19	6	58	36
" 3739	48.26	47.85	48	3	45	26	19	8	58	34
" 3741	45.98	45.50	46	5	41	23	18	2	61	37
" 3742	45.21	44.77	45	0	45	18	27	3	57	40
" 3743	41.70	41.82	42	1	41	19	22	3	61	36
" 3746	46.54	46.84	47	2	45	23	22	8	56	36
" 3749	44.44	43.92	44	4	40	20	20	3	59	38
" 3750	36.95	36.69	37	2	35	16	19	11	51	38
" 3751	46.66	46.44	47	2	45	21	24	4	56	40
" 3752	48.58	48.67	49	3	46	20	26	7	54	39
" 3755	42.49	42.84	43	3	40	20	20	0	67	33
" 3757	38.35	37.61	38	4	34	18	16	2	66	32
" 3760	38.26	38.65	38	4	34	22	12	1	67	32
" 3761	44.51	43.81	44	4	40	23	17	0	64	36
" 3764	42.02	42.10	42	4	38	21	17	1	65	34
" 3783	44.04	44.11	44	-1	45	21	24	0	62	38
" 3786	44.66	44.48	45	2	43	20	23	2	64	34
" 3789	39.11	38.22	39	3	36	17	19	11	58	31
" 3803	38.79	38.24	39	5	34	20	14	10	59	31
" 3847	47.26	47.37	47	-2	49	20	29	2	56	38
" 3850	46.86	47.27	47	0	47	24	23	2	57	41
" 3862	45.17	44.58	45	2	43	20	23	1	63	36
" 3865	43.50	43.13	43	2	41	26	15	1	60	39
" 3867	42.55	43.56	43	1	42	25	17	1	57	42
" 3868	48.35	48.77	49	-3	52	26	26	0	54	46
" 3869	42.13	42.40	42	0	42	21	21	0	65	35
" 3871	38.94	39.16	39	0	39	26	13	1	61	38
" 3872	44.10	44.68	44	-5	49	24	25	0	56	44
" 3873	43.93	43.08	44	-2	46	15	31	0	65	35
" 3876	40.63	40.94	41	1	40	24	16	1	62	31
" 3877	46.50	46.78	47	-5	52	23	29	0	57	43
" 3878	46.23	47.08	47	1	46	20	26	0	64	36
" 3881	45.52	45.09	45	3	42	24	18	1	59	40
" 3882	48.43	48.63	49	-3	52	23	29	0	56	44
" 3883	41.83	45.33	44	1	43	19	24	0	66	34

Table 10. (continued)

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-3886	47.83	47.73	48	5	43	23	20	4	58	38
" 3888	44.18	44.21	44	2	42	23	19	2	61	37
" 3889	50.35	49.60	50	1	49	20	29	0	56	44
" 3890	42.19	42.27	42	1	41	18	23	0	68	32
" 3893	48.43	47.82	48	0	48	20	28	5	48	37
" 3894	44.48	43.88	44	0	44	22	22	3	63	34
" 6661	40.51	40.32	40	-2	42	21	21	0	67	33
" 6668	41.19	41.45	41	0	41	21	20	1	69	30
" 6672	39.17	40.54	40	1	39	21	18	1	69	30
" 6673	30.29	42.26	42	0	42	19	23	0	66	34
" 6677	41.58	41.67	42	3	39	20	19	0	68	32
" 6680	39.09	39.69	39	0	39	19	20	0	70	30
" 6682	45.36	45.74	46	-1	47	17	30	4	61	34
" 6683	42.80	42.71	43	4	39	23	16	0	68	32
" 6685	41.15	41.30	41	1	40	17	23	8	58	34
" 6687	41.04	41.20	41	1	40	24	16	1	67	32
" 6690	39.05	39.66	39	0	39	18	21	4	64	32
" 6692	38.01	38.87	38	-2	40	24	16	0	64	36
" 6695	41.13	41.12	41	2	39	17	22	2	66	32
" 6696	38.66	38.92	39	0	39	16	23	6	62	32
" 6697	40.60	39.98	40	0	40	24	16	1	69	30
" 6705	40.28	40.50	40	3	37	16	21	13	50	34
" 6783	39.95	39.37	40	3	37	22	15	1	67	32
" 6801	40.87	41.58	41	-3	44	19	25	10	55	35
" 6853	40.59	40.21	40	-1	41	17	24	9	52	39
" 6856	41.32	40.21	41	0	41	17	24	9	58	33
" 6863	33.33	34.05	34	-1	35	20	15	12	57	31
" 6869	36.80	36.72	37	-4	41	19	22	3	65	32
" 6872	31.70	31.36	32	1	31	21	10	3	66	31
" 6876	36.35	36.61	37	-4	41	19	21	2	62	36
" 6886	33.94	33.26	34	-3	37	22	15	1	67	32
" 6890	35.23	34.05	35	-2	37	24	13	1	65	34
" 6893	34.59	34.38	34	-3	37	19	18	7	58	30
" 6896	38.66	38.82	39	-3	42	20	22	0	67	33
" 6898	44.30	43.74	44	4	40	25	15	1	65	34
" 6899	40.68	41.78	41	4	37	23	14	1	65	34
" 6901	37.30	37.50	37	-1	38	18	20	0	70	30
" 6902	39.17	39.92	40	1	39	20	19	0	68	32

Table 10. (continued)

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-6904	38.20	38.06	38	2	36	23	13	1	67	32
" 6905	39.98	40.03	40	2	38	22	16	1	67	32
" 6906	39.06	39.83	40	1	39	26	13	1	67	32
" 6907	43.24	42.25	43	3	40	22	18	3	63	34
" 6908	43.50	43.83	44	3	41	22	19	1	68	31
" 6909	40.59	40.22	40	-2	42	20	22	0	64	36

Table 11. Moisture content for 60 in. H_2O moisture tension compared with the liquid limit of silty clay loam soils

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-3630	35.40	35.43	35	-1	36	22	14	2	71	26
" 3634	34.15	33.80	34	-1	35	21	14	0	76	24
" 3635	34.79	34.50	35	0	35	21	14	0	76	24
" 3640	36.01	35.81	36	-2	38	21	17	0	72	28
" 3733	34.82	34.83	35	-2	37	19	18	11	59	29
" 3744	32.55	32.75	33	-3	36	15	21	16	54	30
" 3754	35.35	34.78	35	0	35	23	12	2	72	26
" 3763	32.42	31.65	32	0	32	20	12	1	69	30
" 3776	33.05	33.10	33	-1	34	20	14	4	66	30
" 3777	29.82	29.86	30	0	30	21	9	4	70	26
" 3778	32.27	32.41	32	0	32	22	10	5	72	23
" 3779	31.65	31.77	32	-5	37	18	19	2	70	28
" 3780	30.89	31.70	31	-3	34	21	13	2	76	22
" 3781	35.39	35.93	36	3	33	25	8	2	74	24
" 3782	34.86	35.04	35	3	32	22	10	1	69	30
" 3792	33.07	-j	33	2	31	21	10	14	61	25
" 3794	30.57	30.64	31	0	31	20	11	10	66	24
" 3795	31.32	31.56	31	-1	32	18	14	10	67	23
" 3809	28.06	27.75	28	-1	29	18	11	7	71	22
" 3810	30.26	30.53	30	2	28	18	10	20	58	22

[j]Data for duplicate not available.

Table 11. (continued)

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-3811	28.46	28.71	29	3	26	20	6	9	71	20
" 3814	34.58	34.79	35	0	35	19	16	6	65	29
" 3816	34.93	34.85	35	1	34	19	15	7	67	26
" 3817	33.98	34.14	34	-1	35	20	15	8	65	27
" 3818	30.09	30.01	30	-1	31	16	15	9	68	23
" 3826	28.57	28.94	29	1	28	18	10	26	51	23
" 3855	34.94	35.28	35	0	35	23	12	13	62	24
" 3844	30.76	30.73	31	1	30	21	9	8	61	29
" 3849	36.34	36.17	36	-2	38	21	17	8	64	28
" 3937	34.25	34.28	34	0	34	22	12	2	72	26
" 3938	37.79	38.68	38	-1	39	23	16	1	73	24
" 3940	36.75	36.12	36	0	36	23	13	2	72	26
" 3941	37.09	35.97	36	-1	37	21	16	1	70	28
" 3942	38.48	38.80	39	3	36	24	12	1	76	23
" 3943	38.30	38.56	38	0	38	25	13	2	72	25
" 3944	40.36	41.79	41	2	39	23	16	2	74	23
" 3945	35.23	36.19	36	-1	37	21	16	2	74	24
" 3947	36.28	36.44	36	2	34	20	14	1	76	24
" 3957	43.43	42.96	43	0	43	25	18	14	56	29
" 6543	48.59	49.06	49	3	46	25	21	2	69	29
" 6750	26.88	26.94	27	-1	28	18	8	2	78	20
" 6751	28.46	29.05	29	0	29	20	9	1	77	22
" 6755	29.89	30.03	30	-1	31	18	13	1	71	28
" 6756	35.39	34.55	35	0	35	23	12	1	71	28
" 6759	28.29	28.52	28	1	27	19	8	2	78	20
" 6762	29.80	29.54	30	1	29	19	10	4	73	22
" 6778	29.05	29.09	29	-2	31	19	12	1	73	26
" 7784	35.12	34.48	35	-4	39	20	19	0	71	29
" 6785	29.90	29.57	30	-1	31	17	14	1	69	28
" 6787	30.42	30.43	30	-4	34	18	16	1	75	24
" 6802	33.41	33.01	33	2	31	22	9	7	68	25
" 6803	33.59	34.46	34	0	34	21	13	19	52	29
" 6855	39.37	39.57	39	1	38	21	17	18	58	24
" 6862	25.51	25.35	25	0	25	13	12	39	40	21
" 7008	33.99	34.16	34	0	34	17	17	17	54	29
" 7015	30.31	30.46	30	1	29	16	13	24	51	25
" 7039	36.78	37.34	37	2	35	23	12	1	77	22
" 7042	31.70	31.54	32	-1	33	21	12	1	77	22
" 7043	41.01	40.76	41	5	36	24	12	1	71	28

Table 11. (continued)

Sample[a*] number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-7044	35.47	35.66	36	1	35	21	14	0	74	26
" 7045	34.48	34.91	35	-1	36	21	15	0	74	26
" 7046	31.26	32.09	32	-1	33	22	11	0	78	22
" 7047	35.09	35.47	35	0	35	21	14	0	70	30
" 7048	34.02	33.44	34	-1	35	21	14	1	75	24
" 7049	33.76	33.91	34	-3	37	19	18	1	73	26
" 7050	33.22	33.54	33	-2	35	23	12	1	72	27
" 7051	34.92	35.14	35	-2	37	22	15	0	74	26
" 7052	36.12	36.04	36	2	34	20	14	0	73	27
" 7053	35.73	35.12	35	1	34	20	14	0	74	26
" 7054	36.81	36.50	37	0	37	22	15	0	72	28
" 7055	34.37	34.58	34	0	34	23	11	0	74	24
" 7056	38.15	39.09	39	4	35	23	12	1	69	39
" 7057	33.45	34.04	34	-1	35	21	14	0	77	23
" 7058	36.79	37.65	37	0	37	23	14	0	76	74
" 7059	34.47	34.52	34	1	33	22	11	0	78	22
" 7060	37.17	37.25	37	4	33	21	12	0	74	26
" 7061	34.92	35.33	35	0	35	20	15	0	78	22
" 7062	35.46	35.67	36	0	36	20	16	0	74	26
" 7063	35.02	34.84	35	-1	36	19	17	0	75	25
" 7064	34.12	34.67	34	-2	36	21	15	0	74	26
" 6560	37.18	37.72	37	2	35	20	15	0	70	30
" 6561	37.83	37.40	38	0	38	20	18	0	72	28
" 6562	37.37	37.72	38	3	35	19	16	0	70	30
" 6564	45.57	45.41	46	-2	48	27	21	0	71	29
" 6565	34.05	34.51	34	0	34	21	13	1	78	21
" 6568	37.43	37.61	38	2	36	18	18	7	64	29
" 6573	58.51	57.56	58	-1	59	41	18	7	69	23
" 6574	37.18	41.04	39	4	35	20	15	3	70	27
" 6578	34.85	35.97	35	0	35	19	16	1	75	24
" 6582	35.83	36.71	36	0	36	19	17	0	72	28
" 6583	37.15	37.37	37	0	37	18	19	1	71	28
" 6599	40.95	40.05	41	4	37	24	13	7	63	30
" 6610	35.43	35.85	36	2	34	19	15	1	73	26
" 6614	38.61	31.98	35	-1	36	21	15	1	74	25
" 6615	31.20	32.06	32	2	30	19	11	2	70	28
" 6619	29.50	28.92	29	2	27	18	9	6	67	27
" 6657	41.48	41.62	42	2	40	24	16	0	70	30

Table 11. (continued)

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-6662	32.04	31.50	32	2	30	20	10	0	78	22
" 6663	37.16	36.13	37	0	37	23	14	9	64	27
" 6667	38.71	38.71	39	2	37	24	13	2	74	24
" 6671	32.21	32.82	32	-3	35	17	18	0	76	24
" 6676	34.70	34.67	35	1	34	23	11	0	71	29
" 6678	35.71	36.10	36	-1	37	20	17	0	72	28
" 6679	38.32	38.61	38	-2	40	19	21	0	71	29
" 6681	39.30	38.45	39	0	39	19	20	0	71	29
" 6684	37.81	37.67	38	-1	39	19	20	1	70	29
" 6688	37.77	37.17	37	-1	38	22	16	0	76	24
" 6689	37.29	36.38	37	1	36	20	16	0	74	26
" 6693	37.26	36.44	37	2	35	20	15	0	72	28
" 6694	36.85	37.13	37	0	37	18	19	0	73	27
" 6698	36.99	37.34	37	-3	40	20	20	1	73	26
" 6699	37.57	37.05	37	1	36	17	19	6	64	30
" 6703	35.12	38.64	37	1	36	20	16	1	73	26
" 6704	38.93	38.49	39	1	38	19	19	1	71	28
" 6713	34.80	34.74	35	2	33	23	10	16	62	21
" 6716	39.39	39.30	39	0	39	25	14	11	65	24
" 6725	40.40	40.56	41	0	41	25	16	2	69	29
" 6740	33.75	33.58	34	3	31	19	12	4	68	28
" 7065	32.41	32.08	32	-1	33	21	12	0	78	22
" 7066	34.01	34.00	34	-1	35	22	13	0	77	23
" 7067	35.70	35.88	36	-1	37	20	17	0	74	26
" 7068	35.10	34.99	35	-2	37	21	16	0	72	28
" 7069	38.20	37.41	38	0	38	23	15	0	70	30
" 7070	31.50	31.57	32	0	32	17	15	22	53	25
" 7100	39.38	38.92	39	3	36	24	12	5	63	29
" 7103	31.71	31.39	32	1	31	20	11	1	77	22
" 7105	32.92	32.62	33	-1	34	19	15	0	75	25
" 7106	30.05	33.13	32	0	32	18	14	17	51	23
"" 7110	33.48	33.27	33	-1	34	19	15	0	73	27
" 7114	33.17	32.80	33	0	33	21	12	1	73	26
" 7116	31.08	31.56	31	1	30	22	8	1	78	21
" 7117	28.13	28.24	28	1	27	19	8	1	78	21
" 7118	29.95	29.82	30	2	28	19	9	1	74	25
" 7122	29.49	29.67	30	1	29	19	10	1	76	23
" 7162	37.64	37.16	37	-1	38	23	15	1	70	29

Table 11. (continued)

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-7165	41.58	42.18	42	3	39	23	16	1	71	28
" 7166	36.51	37.65	37	-1	38	22	16	0	70	30
" 7167	31.08	30.50	31	0	31	20	11	0	78	22
" 7176	28.00	27.80	28	-1	29	20	9	1	77	22
" 7184	34.02	34.14	34	-3	37	23	14	13	57	30
" 7189	34.17	33.05	34	0	34	23	11	7	71	22
" 7210	30.60	30.47	31	-2	33	18	15	24	52	23

Table 12. Moisture content for 60 in. H_2O moisture tension compared with the liquid limit of clay loam

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-3601	36.04	35.82	36	0	36	23	13	38	40	22
" 3602	32.61	32.29	32	-1	33	15	18	45	27	25
" 3604	35.71	35.81	36	-1	37	22	15	30	42	28
" 3606	33.33	33.36	33	-3	36	16	20	40	29	26
" 3607	25.37	25.82	26	-2	24	13	11	43	28	20
" 3608	24.93	-[j]	25	1	24	13	11	39	34	20
" 3609	41.35	40.73	41	-1	42	23	19	29	42	29
" 3610	33.06	32.90	33	-2	35	14	21	38	33	25
" 3611	26.12	26.26	26	2	24	14	10	41	34	20
" 3613	36.21	35.58	36	-1	37	18	19	37	34	27
" 3623	29.34	28.93	29	1	28	18	10	37	39	21
" 3626	25.62	25.04	25	0	25	12	13	38	33	19
" 3628	31.99	31.94	32	-1	33	19	14	29	44	27
" 3644	37.55	37.72	38	1	37	21	16	20	49	29
" 3646	28.19	27.88	28	0	28	14	14	46	28	24
" 3650	36.01	35.94	36	1	35	20	15	29	41	30

[j]Data for duplicate not available.

Table 12. (continued)

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-3651	36.73	36.30	36	1	35	22	13	29	42	28
" 3652	30.46	30.52	30	0	30	17	13	44	32	22
" 3653	36.97	37.56	36	-4	40	20	20	39	31	26
" 3656	32.17	32.36	32	0	32	19	13	34	39	27
" 3657	24.67	25.07	25	-1	26	13	13	39	36	20
" 3661	30.26	30.49	30	-1	31	19	12	38	37	25
" 3664	35.17	34.96	35	-1	36	14	22	44	29	24
" 3665	33.74	33.84	34	0	34	22	12	35	35	27
" 3668	27.96	27.32	28	1	27	13	14	40	32	31
" 3669	34.12	33.70	34	-3	37	19	18	38	37	25
" 3738	28.41	28.51	28	0	28	14	14	45	33	22
" 3748	28.41	28.82	29	0	29	14	15	39	35	26
" 3759	29.59	29.27	29	0	29	14	15	36	36	26
" 3765	27.53	27.50	28	0	28	18	10	46	33	21
" 3767	28.94	28.91	29	-1	30	18	12	44	32	22
" 3768	30.89	30.60	31	1	30	19	11	41	35	23
" 3773	28.30	28.25	28	-1	29	14	15	45	33	20
" 3784	30.58	30.47	31	1	30	15	15	31	45	24
" 3828	26.14	25.82	26	1	25	13	12	43	37	20
" 3832	33.71	33.52	34	0	34	16	18	28	44	28
" 3834	26.15	25.90	26	1	25	15	10	45	32	22
" 3836	30.70	30.62	31	3	28	14	14	37	30	25
" 3838	29.95	29.67	30	2	28	15	13	31	37	23
" 3842	31.92	31.26	31	0	31	17	14	30	40	28
" 3507	29.28	28.87	28	-4	32	18	14	36	37	25
" 3511	24.54	23.77	24	-1	25	12	13	43	35	20
" 3512	23.54	24.16	24	1	23	13	10	41	33	21
" 3561	22.71	23.61	23	-1	24	13	11	40	33	21
" 3562	28.73	28.69	29	-2	31	19	12	48	28	24
" 3568	26.32	26.57	26	-3	29	17	12	50	26	24
" 3570	24.39	24.66	24	1	23	16	7	25	43	28
" 3571	28.05	28.05	28	-1	29	16	13	45	29	20
" 3578	31.80	31.66	32	1	31	16	15	38	34	28
" 3584	31.94	33.07	32	1	31	17	14	34	41	23
" 3586	31.30	30.82	31	-2	33	15	18	42	31	24
" 3587	27.70	27.96	28	4	24	14	10	41	33	21
" 3589	29.34	29.40	29	-2	31	15	16	43	28	22
" 3592	26.82	26.30	26	1	25	13	12	41	31	23
" 3593	26.80	28.05	27	2	25	13	12	50	29	21
" 3595	33.36	32.63	33	-1	34	21	13	39	36	24

Table 12. (continued)

Sample[a*] number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sag[g]	si[h]	c[i]
AAD4-3507[k]	31.30	32.11	32	0	32	18	14	36	37	25
" 3511[k]	24.77	24.75	25	0	25	12	13	43	35	20
" 6720[k]	27.77	27.69	28	0	28	14	14	40	40	20
" 3561[k]	24.37	24.31	24	0	24	13	11	40	33	21
" 3562[k]	29.18	29.07	29	-2	31	19	12	48	28	24
" 3568[k]	28.33	28.21	28	-1	29	17	12	50	26	24
" 3570[k]	24.72	24.61	25	2	23	16	7	25	43	28
" 3571[k]	27.58	27.49	28	-1	29	16	13	45	29	20
" 3578[k]	30.84	30.73	31	0	31	16	15	38	34	28
" 3584[k]	30.69	30.76	31	0	31	17	14	34	41	23
" 3586[k]	30.75	30.43	31	-2	33	15	18	42	31	24
" 3587[k]	26.16	25.73	26	2	24	14	10	41	33	21
" 3589[k]	29.55	29.36	29	-2	31	15	16	43	28	22
" 3592[k]	25.16	25.26	25	0	25	13	12	41	31	23
" 3593[k]	25.65	25.73	26	1	25	13	12	50	29	21
" 3595[k]	35.21	34.88	35	1	34	21	13	39	36	24
" 3596	31.53	31.84	32	-1	33	17	16	38	33	27
" 3598	28.41	28.59	29	0	29	16	13	46	28	23
" 3599	25.00	25.29	25	1	24	13	11	40	32	19
" 3600	24.96	25.39	25	0	25	12	13	41	33	21
" 3846	29.77	28.89	29	-1	30	15	15	44	30	24
" 3858	36.66	36.20	36	-1	37	21	16	22	49	29
" 3859	34.07	34.12	34	-3	37	17	20	27	43	29
" 3864	32.66	31.83	32	-1	33	17	16	37	36	24
" 3895	32.71	31.70	32	-8	40	18	22	27	37	36
" 3898	32.92	32.67	33	1	32	21	11	34	39	27
" 3911	38.44	39.07	39	-2	41	24	17	32	38	29
" 3914	23.80	24.21	24	0	24	12	12	44	30	20
" 3919	34.03	33.82	34	-3	37	20	17	36	37	27
" 3949	33.30	33.85	34	0	34	21	13	42	37	21
" 3953	28.70	29.44	29	1	28	18	10	43	34	23
" 3956	34.42	34.74	35	-2	37	14	23	43	31	24
" 3959	35.60	34.99	35	-2	37	21	16	33	41	25
" 6587	32.92	34.91	33	-1	34	14	20	43	27	29
" 6588	29.17	29.27	29	0	29	13	16	37	36	27
" 6592	38.33	38.27	38	-2	40	16	24	28	40	29
" 6600	27.06	27.07	27	-1	28	14	14	46	27	26
" 6604	34.06	34.57	34	-1	35	14	21	33	35	27
" 6606	31.24	31.15	31	-1	32	16	16	25	46	26
" 6670	26.78	26.15	27	0	27	12	15	42	34	22

[k]Rerun of samples above at a later date.

Table 13. Moisture content for 70 in. H_2O moisture tension compared with the liquid limit of loam

Sample number[a*]	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-6866	23.26	22.97	23	0	23	16	7	34	46	20
" 6966	29.48	29.61	30	0	30	19	11	40	40	18
" 7012	23.27	23.50	23	-1	24	13	11	46	37	17
" 7206	26.56	26.36	26	1	25	17	8	37	48	14
" 7218	24.98	25.11	25	0	25	15	10	43	38	19
" 3567	23.59	23.33	23	0	23	15	8	38	41	19
" 3573	24.51	23.82	24	0	24	12	12	42	36	19
" 3576	24.33	24.39	24	2	22	14	8	40	37	17
" 3577	19.65	20.17	20	2	18	15	3	46	38	11
" 3612	24.31	24.09	24	1	23	13	10	39	37	19
" 3621	24.49	25.01	25	3	22	13	9	42	35	15
" 3629	26.14	26.14	26	1	25	14	11	44	35	18
" 3667	27.19	27.09	27	1	26	12	14	41	43	13
" 3769	26.26	25.56	26	0	26	18	8	47	34	19
" 3788	21.73	22.32	22	1	21	16	5	41	46	13
" 3801	23.65	23.38	23	1	22	15	7	44	38	18
" 3807	26.48	26.55	27	-1	28	14	14	32	49	19
" 3808	22.90	23.78	23	1	22	14	8	47	39	14
" 3825	29.97	29.79	30	0	30	20	10	39	43	17
" 3830	24.52	25.33	25	0	25	12	13	43	37	20
" 3833	25.20	25.04	25	0	25	14	11	43	39	18
" 3863	29.00	28.37	29	1	28	18	10	36	44	19
" 3954	-[j]	27.34	27	-1	28	15	13	38	38	19
" 6570	27.08	27.28	27	1	26	18	8	2	78	20
" 6666	24.75	24.55	25	-1	24	14	12	41	37	19
" 6715	24.75	24.86	25	-1	26	13	13	45	37	17
" 6719	24.62	24.52	25	-1	26	15	11	35	49	16
" 6723	24.02	24.01	24	0	24	15	9	36	49	15
" 6729	25.71	25.57	26	0	26	15	11	37	45	17
" 6736	24.05	24.02	24	0	24	14	10	44	39	17
" 6966	30.31	30.05	30	0	30	19	11	40	40	18
" 3230	22.90	22.97	23	-1	24	16	8	43	38	19

[j]Data for duplicate not available.

Table 14. Moisture content for 70 in. H_2O moisture tension compared with the liquid limit of silty loam

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-3603	25.60	25.28	26	1	25	19	6	26	58	16
" 3753	25.45	25.46	25	-1	26	19	7	21	65	14
" 3785	24.55	24.63	24	0	24	19	5	30	53	17
" 3802	28.60	28.74	28	3	25	20	5	19	62	19
" 3804	26.88	26.95	27	1	26	19	7	5	78	17
" 3603[k]	25.50	25.32	25	0	25	19	6	26	58	16
" 3753[k]	25.31	25.90	26	0	26	19	7	21	65	14
" 3785[k]	24.81	24.94	25	1	24	19	5	30	53	17
" 3802[k]	26.95	27.30	27	2	25	20	5	19	62	19
" 3804[k]	27.53	27.78	28	2	26	19	7	5	78	17
" 3815	24.77	25.09	25	0	25	17	8	33	51	16
" 3819	25.74	25.91	26	1	25	16	9	19	63	17
" 3854	29.65	29.65	30	1	29	25	4	15	72	13
" 3916	25.02	24.84	25	-2	27	15	12	31	53	16
" 6590	26.20	26.38	26	0	26	18	8	7	74	19
" 6877	22.70	22.56	23	2	21	17	4	32	55	13
" 6891	28.25	28.12	28	1	27	18	9	9	71	19
" 8235	25.92	25.97	26	0	26	21	5	8	77	15
" 8241	28.03	28.13	28	-1	29	21	8	9	75	16
" 8292	29.18	29.04	29	0	29	20	9	1	79	20
" 6669	28.51	27.78	28	1	27	19	8	0	81	19
" 6709	24.78	24.40	25	-1	26	16	1	26	58	16
" 6712	25.99	25.89	26	0	26	17	9	12	68	20
" 6733	24.07	24.19	24	1	23	17	6	24	60	16
" 6741	28.07	28.00	28	-2	30	18	12	10	71	19
" 6877[k]	21.01	21.27	21	0	21	17	4	32	55	13
" 6891[k]	26.89	26.78	27	0	27	18	9	9	71	19
" 8235[k]	24.21	24.29	24	-2	26	21	5	8	77	15
" 8241[k]	27,62	27.29	28	-1	29	21	8	9	75	16
" 8292[k]	28.24	28.61	29	0	29	20	9	1	79	20
" 8293	27.04	28.40	28	0	28	20	8	1	79	20
" 8299	26.03	26.42	26	-1	27	18	9	10	72	18

[k]Rerun of samples above at a later date.

Table 15. Moisture content for 70 in. H_2O moisture tension compared with the liquid limit of sandy loam

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-3590	32.17	32.45	32	-2	34	21	13	47	29	19
" 3624	22.19	22.26	22	1	21	13	8	53	29	12
" 3627	25.58	25.98	26	0	26	17	9	52	29	16
" 3645	26.13	25.77	26	-1	27	15	12	51	26	16
" 3654	18.56	18.67	19	1	18	14	4	54	33	8
" 3770	19.47	19.62	20	1	19	13	6	66	17	10
" 3787	18.42	18.73	19	1	18	12	6	69	19	12
" 3790	19.01	18.90	19	2	17	13	4	62	27	11
" 3791	18.27	18.32	18	2	16	12	4	61	30	9
" 3797	15.59	15.44	16	1	15	13	2	74	18	8
" 3798	17.53	17.17	17	-1	18	13	5	67	24	9
" 3799	22.58	22.46	23	0	23	13	10	55	29	16
" 3800	17.09	16.95	17	1	16	14	2	50	41	9
" 3805	17.88	17.97	18	0	18	13	5	70	20	10
" 3806	14.56	14.88	15	1	14	13	1	69	22	9
" 3812	19.85	19.89	20	2	18	13	5	58	29	13
" 3813	16.98	17.14	17	1	16	14	2	78	14	8
" 3835	21.87	22.10	22	2	20	14	6	54	35	11
" 3509	24.47	24.53	24	0	24	14	10	50	30	18
" 3564	18.47	18.39	18	1	17	16	1	70	18	12
" 3566	18.91	19.03	19	2	17	15	2	58	33	8
" 3580	25.23	24.82	25	0	25	15	10	52	30	18
" 3583	24.23	23.83	24	1	23	17	6	59	27	14
" 3590[k]	31.65	31.94	32	-2	34	21	13	47	29	19
" 3624[k]	21.16	21.29	21	0	21	13	8	53	29	12

[k]Rerun of samples above at a later date.

Table 16. Moisture content for 70 in. H_2O moisture tension compared with the liquid limit of silt

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-6730	37.51	37.60	38	0	38	24	14	7	88	5
" 6960	30.39	30.07	30	1	29	24	5	1	85	14
" 7040	30.92	31.01	31	0	31	23	8	1	83	16
" 7041	31.25	31.50	31	1	29	23	6	1	81	18
" 7121	29.40	29.55	29	0	29	20	9	0	80	20
" 6730[k]	39.12	39.71	39	1	38	24	14	7	88	5
" 6960[k]	28.77	28.67	29	0	29	24	5	1	85	14
" 7040[k]	32.32	31.81	32	1	31	23	8	1	83	16
" 7041[k]	30.84	31.14	31	2	29	23	6	1	81	18
" 7121[k]	31.28	30.69	31	2	29	20	9	0	80	20
" 7163[l]	29.03	29.02	29	-1	30	20	10	0	82	18

[k]Rerun of group above at a later date.

[l]Run with group above, separated for convenience.

Table 17. Moisture content for 70 in. H_2O moisture tension compared with the liquid limit of gravelly sandy loam

Sample[a*] number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-3556	23.54	23.52	24	2	22	16	6	44	29	15
"										
" 3771	25.99	26.41	26	0	26	17	9	48	23	14
" 7083	18.17	18.11	18	0	18	13	5	68	9	9
" 7086	28.03	27.88	28	0	28	14	14	56	13	13
" 7209	35.95	35.96	36	2	34	21	13	42	27	15
" 8237	23.27	23.52	23	-2	25	13	12	55	18	13
" 8261	17.80	17.78	18	2	16	15	1	52	14	3
" 3771[k]	26.18	25.70	26	0	26	17	9	48	23	14
" 7083[k]	18.96	18.99	19	1	18	13	5	68	9	9
" 7086[k]	27.16	27.44	27	-1	28	14	14	56	13	13
" 7209[k]	35.79	35.35	36	2	34	21	13	42	27	15
" 8237[k]	23.12	23.26	23	-2	25	13	12	55	18	13
" 8261[k]	17.30	17.57	17	1	16	15	1	52	14	3

[k]Rerun of group above at a later date.

Table 18*. Moisture content for 60 in. H_2O moisture tension compared with the liquid limit of soils from various groups run together

Sample number	Group	% Moisture 1	% Moisture 2	Ave.	Dev.	ISHC (ASTM) LL	ISHC (ASTM) PL	ISHC (ASTM) PI	Composition sa	Composition si	Composition c
AAD4-9300	gr. sa[a]	28.01	28.61	28	1	27	18	9	64	6	3
" 9302	sa. l.[b]	28.04	28.60	28	0	28	16	12	54	25	16
" 9303	"	20.35	20.62	20	2	18	17	1	71	22	7
" 9304	"	25.40	26.03	26	3	23	16	7	69	17	13
" 9308	gr. sa. l.[c]	26.70	27.04	27	4	23	15	8	64	14	10
" 9311	s. c. l.[d]	63.80	65.80	65	-2	67	41	26	3	69	28
" 9312	"	43.70	44.06	44	-2	46	26	20	2	69	29
" 9316	s. c.[e]	47.22	46.51	47	-2	49	21	28	0	68	32
" 9317	"	42.17	43.49	43	0	43	19	24	0	63	37
" 9319	"	43.12	39.53	41	0	41	21	20	5	59	36

*See Table 9 for explanation of column headings.

[a]Gravelly sand.

[b]Sandy loam.

[c]Gravelly sandy loam.

[d]Silty clay loam.

[e]Silty clay.

Table 19. Comparison of liquid limit values rerun by ASTM standard, compared with values taken from records previously run by ASTM standard

Sample number	LL by ASTM run during project	LL by ASTM from records	Deviation[a]
504-6	54	56	-2
507-4	44	45	-1
508-3	54	58	-4
505-4	32	33	-1
500-2	52	54	-2
509-4	37	35	2
413-2	53	53	0
511-4	46	46	0
416-2	44	44	0
AAD4-3897	32	31	1
" 6534	43	41	2
" 6581	47	46	1
" 6793	35	31	4
" 7214	56	56	0
" 7009	34	34	0
" 7010	40	39	1
" 7011	41	39	2
" 7190	38	36	2
" 7192	43	41	2
" 7197	39	36	3
" 6777	44	41	3
" 6779	69	66	3
" 6782	58	56	2
" 6794	33	30	3
" 6796	38	33	5
" 3913	49	45	4
" 6545	56	52	4
" 6579	41	36	5
" 6602	51	49	2
" 6611	41	36	5
" 6653	41	42	-1
" 6658	30	29	1
" 6659	43	43	0
" 6683	44	39	5
" 6705	43	37	6
" 6783	40	37	3
" 3734	46	46	0
" 3796	31	31	0
" 6644	52	53	-1

[a]Values run during project minus record values.

Table 20. Comparison of liquid limit values of two separate moisture tension runs of 60 clays at 40 in. H_2O

Sample number	LL by moisture[a] tension, 12-23-64	LL by moisture tension, 1-23-65	Deviation[b]
AAD4-8266	52	52	0
" 8281	37	37	0
" 8285	36	37	-1
" 8294	35	35	0
" 8315	42	41	1
" 8326	35	37	-2
" 8337	44	44	0
" 8342	37	38	-1
" 8347	41	41	0
" 8402	39	39	0
" 8415	42	41	1
" 8416	48	50	-2
" 8423	37	37	0
" 8428	36	37	-1
" 8438	37	37	0
" 8443	33	34	-1
" 8444	41	42	-1
" 8447	62	63	-1
" 8458	51	52	-1
" 8461	50	50	0
" 8463	41	42	-1
" 8465	40	42	-2
" 8472	46	47	-1
" 8478	42	47	-5
" 8489	50	50	0
" 8491	57	56	1
" 8492	55	55	0
" 8493	62	62	0
" 9017	35	36	-1
" 9018	56	57	-1
" 9019	48	50	-2
" 9036	33	34	-1
" 9041	36	38	-2
" 9055	37	36	1

[a]Values also used in Table 9.

[b]Values from 12-23-64 minus values from 1-23-65.

Table 20. (continued)

Sample number	LL by moisture[a] tension, 12-23-64	LL by moisture tension, 1-23-65	Deviation[b]
AAD4-9064	43	45	-2
" 9065	41	42	-1
" 9067	58	59	-1
" 9068	38	39	-1
" 9069	50	50	0
" 9076	61	62	-1
" 9084	58	59	-1
" 9091	42	41	-1
" 9094	39	39	0
" 9095	86	85	1
" 9097	82	83	-1
" 9101	41	40	1
" 9102	28	28	0
" 9105	35	36	-1
" 9116	51	50	1
" 9120	69	69	0
" 9125	52	52	0
" 9142	66	68	-2
" 9143	71	75	-4
" 9144	73	75	-2
" 9145	75	75	0
" 9190	46	48	-2
" 9196	50	52	-2
" 9199	42	43	-1
" 9203	52	53	-1
" 9215	43	46	-3

Table 21. Moisture content for 162 psi moisture tension compared with the plastic limit of clay soils

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	ci
AAD4-3493	18.59	18.96	19	0	44	19	25	18	43	37
" 3496	18.61	18.49	19	1	45	18	27	23	35	41
" 3505	22.05	22.01	22	0	53	22	31	9	41	50
" 3513	17.23	17.61	17	-2	41	19	22	18	42	36
" 3515	18.90	18.42	19	0	47	19	28	26	31	42
" 3516	17.61	17.36	17	0	42	17	25	22	36	40
" 3518	16.73	16.76	17	2	44	15	29	36	28	35
" 3525	24.17	24.47	24	5	59	19	40	2	42	56
" 3527	18.42	17.84	18	1	45	17	28	25	31	40
" 3528	16.84	16.80	17	2	44	15	29	30	31	37
" 3541	15.66	15.67	16	-6	38	22	16	15	48	37
" 3632	19.96	20.19	20	3	50	17	33	20	39	39
" 3633	17.03	16.56	17	2	41	15	26	26	42	31
" 3637	18.74	18.15	18	0	42	18	24	18	48	33
" 3638	18.60	18.65	19	1	45	18	27	28	34	37
" 3658	24.22	22.97	23	0	47	23	24	14	43	43
" 3659	25.00	21.29	23	3	49	20	29	15	43	96
" 3662	23.04	22.90	23	-3	47	26	21	21	39	39
" 3663	21.11	21.19	21	1	49	20	29	21	38	40
" 3670	19.21	16.97	18	-2	39	20	19	29	38	33
" 3674	17.98	17.75	18	3	46	15	31	26	34	39
" 3678	22.79	22.33	23	7	56	16	40	13	40	47
" 3679	19.29	19.62	20	3	51	17	34	25	32	43
" 3680	21.75	21.60	22	5	56	17	39	9	41	50
" 3684	28.62	28.49	29	6	67	23	44	3	27	70
" 3730	19.25	21.57	20	3	47	17	30	11	47	40
" 3731	21.47	23.54	22	2	51	20	31	2	50	48
" 3736	15.83	15.49	16	1	38	15	23	33	31	35
" 3737	18.28	18.16	18	1	45	17	28	12	44	43
" 3740	17.19	16.71	17	2	42	15	27	33	28	39
" 3745	15.73	15.94	16	-4	38	20	18	16	50	34
" 3747	15.63	15.57	16	1	36	15	21	25	38	34
" 3827	15.44	14.04	15	-3	34	18	16	24	43	33
" 3831	16.05	15.71	16	0	36	16	20	21	43	36
" 3840	12.84	12.76	13	-2	32	15	17	27	39	30
" 3843	16.83	16.65	17	0	38	17	21	34	29	34
" 3848	14.43	14.68	15	-4	38	19	19	15	47	33
" 3853	29.19	28.57	29	2	78	27	51	0	24	76

Table 21. (continued)

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-3861	19.53	20.04	20	0	46	20	26	25	37	37
" 3870	20.86	20.57	21	1	48	20	28	21	36	43
" 3874	21.34	21.25	21	3	51	18	33	14	39	47
" 3875	18.61	18.25	18	2	44	16	28	27	36	37
" 3879	20.98	19.75	20	3	46	17	29	15	42	43
" 3880	19.32	19.94	20	3	48	17	31	22	37	41
" 3884	19.30	18.99	19	1	43	18	25	17	42	41
" 3885	19.38	19.66	20	1	47	19	28	23	34	43
" 3891	14.98	15.14	15	1	35	14	21	30	38	32
" 3892	19.16	19.00	19	3	43	16	27	13	44	43
" 3896	18.60	18.60	19	1	40	18	22	27	37	36
" 3912	21.70	22.17	22	0	46	22	24	25	39	36
" 3915	21.32	20.63	21	2	47	19	28	11	44	46
" 3950	27.41	26.09	27	0	57	27	30	21	36	42
" 3951	19.39	20.02	20	1	46	19	27	21	41	36
" 6518	22.01	21.63	22	1	57	21	36	12	38	50
" 6520	27.95	26.84	27	3	67	24	43	2	47	51
" 6524	22.66	22.20	22	-6	52	28	24	12	50	38
" 6526	16.12	15.83	16	1	37	15	22	30	27	40
" 6531	19.66	19.97	20	4	47	16	31	10	48	42
" 6532	18.69	18.24	18	4	48	14	34	19	39	41
" 6534	22.43	20.76	21	-4	41	25	16	24	44	32
" 6536	15.80	15.54	16	1	37	15	22	29	32	35
" 6537	20.48	20.26	20	-2	41	22	19	22	40	38
" 6539	15.70	15.86	16	3	39	13	26	31	30	38
" 6540	22.32	20.56	21	0	44	21	23	21	40	39
" 6541	18.16	18.05	18	2	45	16	29	28	27	42
" 6546	17.86	17.59	18	2	48	16	32	27	30	42
" 6547	16.96	19.79	17	2	41	15	26	30	32	37
" 6581	18.07	17.66	18	4	46	14	32	19	37	43
" 6589	16.20	16.21	16	2	39	14	25	28	39	33
" 6758	15.71	15.82	16	0	28	16	12	16	45	39
" 6766	21.51	21.25	21	3	48	18	30	13	25	58
" 6792	21.29	21.47	21	-1	42	22	20	1	39	60
" 6795	14.58	14.40	14	-4	33	18	15	26	43	30
" 6798	15.65	15.67	16	2	33	14	19	31	40	24
" 6800	18.23	18.22	18	2	39	16	23	34	29	36
" 6804	15.51	15.71	16	-2	35	14	21	42	24	32

Table 22. Moisture content for 70 psi moisture tension compared with the plastic limit of silty clay soils

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-3917	20.56	20.72	21	3	37	18	19	4	58	38
" 3939	18.79	18.78	19	-6	42	25	17	1	69	30
" 3964	21.66	21.25	21	-1	41	22	19	2	64	34
" 3952	22.06	21.95	22	1	44	21	23	12	57	31
" 6519	30.18	29.83	30	3	53	27	26	3	51	46
" 6527	25.21	24.53	25	-1	49	26	23	2	59	39
" 6528	23.85	23.81	24	5	45	19	26	3	59	38
" 6529	22.35	22.34	22	6	41	16	25	7	54	39
" 6548	24.48	23.41	24	0	45	24	21	2	60	38
" 6551	22.44	22.76	23	-6	46	29	17	13	53	34
" 6552	26.51	26.43	26	2	46	24	22	7	51	42
" 6555	24.20	24.94	25	0	49	25	24	11	53	36
" 6559	21.94	22.02	22	0	41	22	19	1	64	35
" 6569	12.93	12.64	13	-7	31	20	11	8	73	19
" 6580	20.12	20.06	20	6	36	14	22	16	52	31
" 6584	22.71	23.02	23	7	41	16	25	6	58	36
" 6585	18.71	18.75	19	-6	40	25	15	1	67	32
" 6586	19.49	19.66	20	-1	38	21	17	1	67	32
" 6605	17.34	17.39	17	1	33	16	17	24	46	28
" 6609	18.12	18.18	18	-1	40	19	21	1	68	31
" 6613	20.00	19.86	20	0	38	20	18	1	68	31
" 6616	18.74	18.53	19	-6	40	25	15	1	65	34
" 6617	17.40	17.13	17	-14	41	31	10	1	67	32
" 6620	16.89	17.34	17	-4	39	21	18	2	68	30
" 6650	17.99	18.17	18	-6	39	24	15	1	58	41
" 6651	19.13	19.76	19	-6	40	25	15	1	67	32
" 6652	19.07	19.03	19	-3	39	22	17	1	66	33
" 6653	20.62	20.63	21	0	42	21	21	0	68	32
" 6654	20.40	18.46	19	-5	42	24	18	0	68	32
" 6655	17.80	17.77	18	-6	40	24	16	0	66	34
" 6656	17.38	17.35	17	-7	41	24	17	1	69	30
" 6660	16.09	16.21	16	-6	34	22	12	1	67	32
" 6661	21.38	21.34	21	0	42	21	21	0	67	33
" 6668	20.18	19.09	20	-1	41	21	20	1	69	30
" 6672	17.17	17.47	17	-4	39	21	18	1	69	30
" 6673	19.89	19.72	20	1	42	19	23	0	66	34
" 6677	21.27	20.22	21	1	39	20	19	0	68	32
" 6680	19.30	19.22	19	0	39	19	20	0	70	30
"" 6682	23.89	24.28	24	7	47	17	30	4	61	34

Table 22. (continued)

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-6685	21.33	21.52	21	4	40	17	23	8	58	34
" 6687	20.69	23.05	22	-2	40	24	16	1	67	32
" 6690	21.32	22.32	22	4	39	18	21	4	64	32
" 6692	19.27	19.66	19	-5	40	24	16	0	64	36
" 6695	20.07	23.05	22	5	39	17	22	2	66	32
" 6696	20.25	20.16	20	4	39	16	23	6	62	32
" 6697	17.94	17.28	18	-6	40	24	16	1	69	30
" 6853	22.69	22.44	23	6	41	17	24	9	52	39
" 6856	20.76	21.08	21	4	41	17	24	9	58	33
" 6863	19.59	19.46	20	0	35	20	15	12	57	31
" 6872	12.02	14.08	13	-8	31	21	10	3	66	31
" 6890	20.45	18.27	19	-5	37	24	13	1	65	34
" 6901	19.42	18.70	18	0	38	18	20	0	70	30
" 6902	18.50	19.38	19	-1	39	20	19	0	68	32
" 6904	17.57	19.44	19	-4	36	23	13	1	67	32
" 6905	18.52	18.28	18	-4	38	22	16	1	67	32
" 6906	23.33	27.85	23	-3	39	26	13	1	67	32
" 6909	19.43	19.18	19	-1	42	20	22	0	64	36
" 6911	19.19	19.37	19	1	38	18	20	0	68	32
" 6913	16.61	16.94	17	-5	40	22	18	1	64	35
" 6916	17.71	17.75	18	-9	41	27	14	1	67	22
" 6917	20.68	22.54	21	1	40	20	20	0	68	32
" 6922	18.32	17.97	18	-6	40	24	16	14	53	33
" 6923	11.13	11.02	11	-9	28	20	8	0	56	44
" 6924	20.39	20.07	20	0	43	20	23	1	66	33
" 6925	18.44	18.55	18	-5	42	23	19	1	65	34
" 6926	17.28	17.81	17	-5	36	23	15	1	64	35
" 6930	17.91	17.44	18	-5	39	23	16	1	67	32
" 6937	20.81	21.10	21	2	44	19	25	2	64	34
" 6942	19.70	20.07	20	3	42	17	25	1	65	34
" 6967	24.94	23.68	24	5	44	19	25	6	57	37
" 7038	18.10	17.86	18	-5	39	23	16	1	66	33
" 7072	15.39	15.12	15	-7	37	22	15	3	66	31
" 7073	18.42	17.79	18	-1	38	19	19	3	63	34
" 7074	26.13	25.87	26	4	52	22	30	0	60	40
" 7075	23.24	22.74	23	4	43	19	24	2	65	33
" 7077	20.69	20.90	21	-1	42	22	20	3	57	40
" 7078	24.88	24.98	25	6	49	18	31	1	60	39
" 7084	20.40	20.62	21	-1	42	22	20	1	63	36

Table 23. Moisture content for 35 psi moisture tension compared with the plastic limit of silty clay loam

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-3811	20.01	19.89	20	0	26	20	6	9	71	20
" 3814	19.05	18.94	19	0	35	19	16	6	65	29
" 3816	19.24	19.22	19	0	34	19	15	7	67	26
" 3817	20.53	20.55	21	1	35	20	15	8	65	27
" 3818	17.73	17.93	18	2	31	16	15	9	68	23
" 3826	16.37	16.24	16	-2	28	18	10	26	51	23
" 3844	17.90	17.69	18	-3	30	21	9	8	61	29
" 3849	21.60	21.42	22	1	38	21	17	8	64	28
" 3855	16.96	16.60	17	-6	35	23	12	13	62	24
" 3937	18.75	18.65	19	-3	34	22	12	2	72	26
" 3938	20.18	20.45	20	-3	39	23	16	1	73	24
" 3940	23.55	23.73	24	1	36	23	13	2	72	26
" 3941	23.76	23.52	24	3	37	21	16	1	70	28
" 3942	20.12	20.18	21	-3	36	24	12	1	76	23
" 3943	22.97	22.62	23	-2	38	25	13	2	72	25
" 3944	21.09	20.87	21	-2	39	23	16	2	74	23
" 3945	22.55	22.48	22	1	37	21	16	2	74	24
" 3947	19.96	19.88	20	0	34	20	14	1	76	24
" 3957	23.28	23.06	23	-2	43	25	18	14	56	29
" 6543	31.56	30.63	30	5	46	25	21	2	69	29
" 6560	24.50	24.48	24	4	35	20	15	0	70	30
" 6561	24.82	25.19	25	5	38	20	18	0	72	28
" 6562	24.05	23.63	24	5	35	19	16	0	70	30
" 6564	29.65	28.19	29	2	48	27	21	0	71	29
" 6565	19.26	19.47	19	-2	34	21	13	1	78	21
" 6568	23.75	23.60	24	6	36	18	18	7	64	29
" 6573	35.18	37.49	36	-5	59	41	18	7	69	23
" 6574	23.77	23.70	24	4	35	20	15	3	70	27
" 6578	20.25	20.18	20	1	35	19	16	1	75	24
" 6582	23.08	24.07	23	4	36	19	17	0	72	28
" 6583	24.85	24.73	25	7	37	18	19	1	71	28
" 6599	20.86	21.31	21	-3	37	24	13	7	63	30
" 6610	20.16	21.44	21	2	34	19	15	1	73	26
" 6614	23.83	23.72	24	3	36	21	15	1	74	25
" 6615	20.70	20.78	21	2	30	19	11	2	70	28
" 6619	17.51	17.65	18	0	27	18	9	6	67	27
" 6657	22.01	20.93	21	-3	40	24	16	0	70	30
" 6662	17.35	17.32	17	-3	30	20	10	0	78	22

Table 23. (continued)

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-6663	20.53	22.91	22	-1	37	23	14	9	64	27
" 6667	19.65	19.89	20	-4	37	24	13	2	74	24
" 6671	20.40	20.22	20	3	35	17	18	0	76	24
" 6676	23.05	21.68	22	-1	34	23	11	0	71	29
" 6678	24.32	24.82	24	4	37	20	17	0	72	28
" 6679	25.50	25.19	25	6	40	19	21	0	71	29
" 6681	21.67	23.13	22	3	39	19	20	0	71	29
" 6684	25.09	25.07	25	6	39	19	20	1	70	29
" 6688	22.74	21.92	22	0	38	22	16	0	76	24
" 6689	21.86	21.49	22	2	36	20	16	0	74	26
" 6693	22.74	22.96	23	3	35	20	15	0	72	28
" 6694	24.98	24.56	25	7	37	18	19	0	73	27
" 6698	21.12	20.91	21	1	40	20	20	11	73	26
" 6699	23.56	23.76	24	7	36	17	19	6	64	30
" 6703	23.56	24.72	24	4	36	20	16	1	73	26
" 6704	25.40	25.04	25	6	38	19	19	1	71	28
" 6713	20.52	20.93	21	-2	33	23	10	16	62	21
" 6716	19.97	17.71	18	-7	39	25	14	11	65	24
" 6725	24.33	24.91	25	0	41	25	16	2	69	29
" 6740	19.60	19.91	20	1	31	19	12	4	68	28
" 6749	21.56	20.53	21	2	34	19	15	0	74	26

Table 24. Moisture content for 70 psi moisture tension compared with the plastic limit of clay loam

Sample number[a*]	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-8245	14.43	14.32	14	-8	33	22	11	26	49	25
" 9140	17.25	16.90	17	-5	37	22	15	22	50	28
" 8247	19.53	19.22	19	3	35	16	19	36	39	25
" 8248	16.99	16.65	17	4	32	13	19	44	30	24
" 8249	16.78	16.86	17	-4	37	21	16	38	37	23
" 8250	19.05	19.14	19	2	35	17	18	32	39	26
" 8252	13.62	13.78	14	-3	31	17	14	35	40	20
" 8253	15.51	15.67	16	1	32	15	17	28	42	25
" 8254	18.63	18.51	19	1	37	18	19	28	44	27
" 8256	14.26	13.91	14	-4	31	18	13	41	37	21
" 8258	18.52	18.04	18	-4	39	22	17	35	41	24
" 8280	15.11	15.20	15	-7	37	22	15	28	48	23
" 8300	17.84	18.04	18	3	32	15	17	31	39	30
" 8308	17.74	17.43	18	4	34	14	20	39	31	28
" 9186	18.77	18.30	19	-2	34	21	13	34	42	24
" 8316	17.73	17.89	18	4	35	14	21	41	32	26
" 8321	16.50	16.17	16	2	32	14	18	35	37	27
" 8329	12.14	12.31	12	0	23	12	11	37	36	22
" 8332	16.85	16.58	17	2	30	15	15	30	41	25
" 8338	17.61	17.36	17	2	32	15	17	33	39	26
" 8349	13.87	13.27	14	-4	30	18	12	38	35	23
" 8362	17.83	17.88	18	3	30	15	15	26	46	27
" 8363	16.98	17.14	17	2	31	15	16	34	34	28
" 8391	14.29	14.29	14	0	28	14	14	35	36	24
" 8392	15.92	15.94	16	2	30	14	16	32	40	27
" 8394	16.37	16.30	16	-1	36	17	19	35	35	27
" 8435	17.70	17.30	17	1	33	16	17	36	32	29
" 8446	13.20	13.38	13	1	26	12	14	47	31	20
" 9020	20.69	20.56	21	-5	44	26	18	36	34	27
" 9026	13.93	14.42	14	0	28	14	14	38	33	23
" 9027	14.53	14.24	14	-1	28	15	13	41	30	22
" 9028	19.35	19.87	20	-2	34	22	12	44	28	25
" 9034	18.09	17.79	18	-3	36	21	15	37	34	27
" 9035	16.27	16.73	17	-3	35	20	15	37	34	27
" 9037	14.39	14.17	14	0	27	14	13	38	37	22
" 9038	26.53	27.26	27	-1	37	28	9	38	35	25
" 9045	16.87	17.16	17	-1	33	18	15	35	35	26
" 9046	17.35	17,24	17	2	31	15	16	25	47	25

Table 24. (continued)

Sample[a]* number	% Moisture[b] 1	2	Ave.[c]	Dev.[d]	ISHC (ASTM)[e] LL	PL	PI	Composition[f] sa[g]	si[h]	c[i]
AAD4-9048	18.00	17.92	18	1	33	17	16	37	36	25
" 9049	18.07	17.61	18	2	33	16	17	38	33	26
" 9052	15.08	14.83	15	-2	29	17	12	41	35	21
" 9053	15.33	15.18	15	-5	36	20	16	38	33	23
" 9057	16.69	16.33	17	-5	39	22	17	38	38	22
" 9058	19.50	19.60	20	4	38	16	22	32	39	27
" 9059	16.91	17.03	17	1	32	16	16	27	45	25
" 9063	17.85	17.53	18	-2	35	20	15	23	46	29
" 9071	17.13	17.22	17	3	34	14	20	33	35	29
" 9074	11.73	11.91	12	-4	27	16	11	45	34	21
" 9075	14.47	14.44	14	-6	32	20	12	28	46	26
" 9079	17.77	17.28	17	1	34	16	18	24	47	29
" 9080	14.70	15.13	15	-5	34	20	14	29	45	26
" 9082	14.69	15.36	15	2	28	13	15	38	39	23
" 9086	13.83	13.76	14	-5	31	19	12	34	42	24
" 9096	17.74	18.18	18	0	38	18	20	30	34	26
" 9107	14.78	15.22	15	1	27	14	13	44	30	22
" 9108	14.55	14.89	15	-8	36	23	13	28	48	24
" 9109	15.39	15.20	15	-4	31	19	12	33	41	26
" 9111	14.72	14.82	15	1	28	14	14	45	31	21
" 9113	15.20	15.51	15	-4	33	19	14	40	36	24
" 9139	14.60	15.06	15	2	26	13	13	44	31	22

Table 25. Comparison of plastic limit values rerun by ASTM standard compared with values taken from records previously run by ASTM standard

Sample number	PL by ASTM run during project	PL by ASTM from records	Deviation
AAD4 8353	21	23	-2
" 8336	15	16	-1
" 8496	21	24	-3
" 8421	20	21	-1
" 8400	17	18	-1
" 8367	18	21	-3

Table 26. Comparison of plastic limit values of two separate moisture tension runs of 20 clays at 70 psi

Sample number	PL by moisture tension, 12-17-64	PL by moisture tension, 1-7-65	Deviation
AAD4-8245	14	15	-1
" 9140	17	17	0
" 8247	19	19	0
" 8248	17	17	0
" 8249	17	17	0
" 8250	19	19	0
" 8252	14	14	0
" 8253	16	16	0
" 8254	19	20	-1
" 8256	14	14	0
" 8258	18	19	-1
" 8280	15	15	0
" 8300	18	18	0
" 8308	18	18	0
" 9186	19	19	0
" 8316	18	18	0
" 8321	16	17	-1
" 8329	12	12	0
" 8332	17	17	0
" 8338	17	18	-1

Table 27. Summary of all liquid limit data presented in Tables 9 through 20

Group	Summary of table	Number of samples	Percentage of samples that are equal to or less than a deviation of: 1	2	3	4	5	6	7	8	9	10	Ave. dev.
clay	9	168[a]	38.6	62.4	79.1	84.5	88.6	94.6	96.4	98.8	99.4	100	2.4
silty clay	10	158	41.8	62.7	81.7	92.5	98.2	99.4	99.4	99.4	100		2.1
silty clay loam	11	142	63.4	83.1	93.0	97.9	99.3	99.3	99.3	100			1.3
clay loam	12	96[b]	71.9	90.7	98.0	100							1.2
loam	13	32	90.6	96.9	100								0.7
silty loam	14	32[c]	78.1	96.8	100								0.9
sandy loam	15	25[d]	72.0	100									1.0
silt	16	11[e]	81.8	100									0.8
gravelly sandy loam	17	13[f]	53.8	100									1.5
combined run	18	10	40.0	80.0	90.0	100							1.7
total all groups	9-18	687	55.9	77.0	88.9	94.3	96.9	98.5	98.8	99.4	99.8	100	1.7
comparison of ASTM method rerun (various)	19	39	43.6	66.7	79.5	89.8	97.5	100					2.0
comparison of moisture tension rerun (clays)	20	60	94.9	96.6	98.3	100							1.0

[a]Includes 18 samples that were run twice.

[b]Includes 15 samples that were run twice.

[c]Includes 10 samples that were run twice.

[d]Includes 2 samples that were run twice.

[e]Includes 5 samples that were run twice.

[f]Includes 6 samples that were run twice.

Table 28. Summary of all plastic limit data presented in Tables 21 through 26

Group	Summary of tables	Number of samples	Percentage of samples that are equal to or less than a deviation of: 1	2	3	4	5	6	7	8	9	10	Average deviation
clay	21	76	39.5	64.5	82.9	92.1	94.7	98.6	100				2.1
silty clay	22	78	33.3	37.1	43.5	56.3	70.5	88.4	94.8	96.1	98.7	100	3.7
silty clay loam	23	59	27.1	47.4	67.7	77.9	84.6	93.1	99.3	100			2.9
clay loam	24	60	30.0	53.3	65.0	83.2	93.2	94.9	96.6	100			2.8
total all groups	21-24	273	33.3	50.9	64.8	77.3	85.7	94.1	98.2	99.3	100		2.7
comparison of ASTM method rerun (various)	25	6	50.0	66.7	100								1.8
comparison of moisture tension rerun (clay loams)	26	20	100										0.3

samples available, would appear to be insufficient for making positive conclusions. However, it can be noted by visual observation of the data of the "groups", or individual runs within the larger textural groups, that they vary in the same proportion as the entire group. It should be reasonable to assume then, that the variance of these groups would have remained essentially the same if a great many more samples had been run.

There is no clear cut criteria to judge a consistency limit value. There is no general agreement as to the magnitude of variance that should be allowable, just as there is no general agreement as to the acceptability of the ASTM standard methods in their present form (5, 6, 17, 18, 26, 27, 29, 30, 32, 34, 43, 47, 50, 51, 59).

Considering the great number of factors that can contribute to variance in the standard methods, it should be reasonable to conclude that calling a liquid limit value 40, instead of 39, or 41, is in a sense "arbitrary". In other words, there is doubt that a "variance" of one is really a variance at all. In his recent (1963) text, Scott (44) expresses this idea as follows:

> "The liquid limit of a soil determined on the basis of such a test should not be expressed in decimals of a percentage; an indication that the liquid limit in a given case is, say 44% or 45%, strains the accuracy of the device to the limit."

For the purpose of establishing some criteria herein for evaluating the liquid limits, it will be assumed that a deviation of two should be universally acceptable and the best that can be expected from reproducing any group of liquid limits is that a large percentage do not vary more than three or four. In this respect, the comparison run (Table 19) in

which 39 samples were rerun by the ASTM standard method and checked against values taken from records (previously run by the ASTM standard method) will arbitrarily be used herein as a guide.

There is every reason to assume that the results obtained in each case were as accurate and reliable as is humanly possible. They do, in fact, show less variance than some reported reproducibility tests (17, 43). Also, see Table 1 of this thesis. Thus the criteria of "acceptable" deviation assumed herein using Table 27 as a guide, would require that:

1. 65 percent of the calculated results be within 2;
2. 80 percent of the calculated results be within 3;
3. 90 percent of the calculated results be within 4; and
4. average deviation should be within 2.

It is not anticipated that everyone would agree with the above criteria. It is contended here; however, that since there is no agreement regarding this variation, that the above criteria is reasonable considering the nature of the standard method with all its inherent shortcomings.

The analysis of 687 samples that represent the study of liquid limits, shows that the results are well within the criteria established above; i.e., 79.5 per cent of the results are within a deviation of 3, 66.7 per cent are within a deviation of 2, and the average deviation is 1.7. Considering the groups individually, there should be no question regarding the clay loams, loams, silty loams, sandy loam groups, as more than 90 percent of all these groups are within a deviation of 2, with average deviations well under 2. The silty clay loam group is slightly more variable, but it is well within both the total group deviation and that of the standard method. The silty clay shows about the

same deviation as that of the standard method. The clay group is the only one showing more deviation than the standard, but only to a slight degree. The clay group, because of its greater variation in composition and properties, should be the most variable by any method. For example, it can be seen by visual observation of Tables 9 (clay) and 15 (sandy loam) that the range of clay liquid limits is from 27 to 77; the range of sandy loam liquid limits is from 21 to 30. Their compositions vary approximately in relative proportion.

The data indicates that the liquid limit results run by the moisture tension method are capable of reproducing the standard results with less variation than the standard method. Considering the moisture tension itself, there is no doubt that it reproduces its own values closely. During the experimental phase of this project, many samples were run a second time; some of these reruns were accidental, others were used as checks. Reruns appear in Tables 9, 12, 14, 15, 16, and 17; the high degree of reproducibility can be easily noted. Also, two groups of 60 and 20 samples each were rerun as a separate test of reproducibility and the results are tabulated in Tables 18 and 24 and analysed in Tables 27 and 28 respectively.

The group that was rerun at 40 inches of water pressure in the pressure plate apparatus showed that the deviation was not greater than one for 94.9 per cent of the results, with a maximum of four and an average of one (Table 27). The second group that was rerun at 70 psi in the pressure membrane apparatus had all of its results within a deviation of one, with an average deviation of 0.3 (Table 28). The 60 samples

run at 40 inches of water pressures were all clays which probably accounts for their greater deviation compared to the second group, which was composed of clay loams.

Any soil sample that is properly ground and consistently prepared for moisture tension runs should result in the same high degree of reproducibility for any number of runs.

The analyses of 687 samples that represent the study of liquid limits, shows that the moisture tension values obtained compare to values obtained by the standard method within the deviation that could be expected within the standard method alone. The samples rerun indicate that the moisture tension method has the capability of reproducing its own values with very little deviation. In other words, the results indicate that the moisture tension method is capable of producing a liquid limit value essentially the same as would be obtained by the standard ASTM method with practically no variation in reproducing the values.

The nature of the method and the equipment keep operator variability to a minimum; it should be negligible. One other factor in favor of the moisture tension method is its speed. In one container of four ceramic plates, 80 duplicate or 160 single samples can be run. One man could possibly handle four such containers a day. Assuming that three sets (12 containers) are available so that the operator can unload four and load four every day; 320 duplicate or 640 single liquid limit values may be obtained per day, on the average. This number is substantially more than would be possible using the standard method.

The discussion above has been concerned with running each group at a "best" pressure as indicated by Table 7. Even though the differences

in pressure are small, it would be more convenient if all groups could be run at one pressure, say 60 inches of water. One run of 10 samples was made combining gravelly sand, sandy loam, gravelly sandy loam, silty clay and silty clay loam. The first three should be run at 70 inches of water, the silty clay loam at 60 inches of water and the silty clay at 40 inches of water. A variation was made in this particular run in that it was timed. It was anticipated that cutting the run off at 24 hours, would leave the silty clays short of equilibrium and tend to compensate for running them at the higher pressure which, at equilibrium, should have resulted in values that were too dry. As for those that should have been run at 70 inches of water (gravelly sand, sandy loam, and gravelly sandy loam) it was hoped that the 10 inches of water pressure difference would have a minor effect on the acceptability of the results.

On the basis of 10 samples, the results were entirely acceptable, with 80 per cent of the results having a deviation less than two, 90 per cent having a deviation less than three, and the group having and average deviation of 1.7. One run of 10 samples should not be used to make definite conclusions. However, it does indicate the possibility that a 24 hour combined run at 60 inches of water pressure has possibilities that should be investigated further.

The results of the plastic limit runs are analysed in Table 28. Much of the general discussion above regarding acceptable deviation and reproducibility of results is also applicable to the plastic limit determination by moisture tension.

The plastic limit values by the standard method are perhaps more variable between different operators than the liquid limit values.

However, to determine a reasonable criteria for evaluating the results is, perhaps, not as easy. Ballard and Weeks (5) pointed out that an operator could reproduce his own result with little variation, but that variation between operators was greater, Less research has been published regarding plastic limit determinations, than is the case with liquid limit studies. A few samples (6) were run by the ASTM standard hand method for comparison to the values from the record. The six results are insufficient for using as a reliable guide. Using the guide used with the liquid limit values, it can be noted that only the clays are close to this criteria, with over 80 per cent of the deviations being within three and an average deviation of 2.1. There is little doubt that the silty clays values could not be accepted, and the silty clay loams and clay loams are questionable.

Observation of the tabulated silty clay data (Table 22) shows that there is wide variance. It can be noted that if a histogram of variations were plotted that the values would have two modes, one at zero (10 values) and another at -6 (also 10 values) with the remaining values widely distributed and showing no central tendency. The clay loams and the silty clay loams also show wide distribution with little or no central tendency. There is no possible way to determine how much of this wide distribution is caused by inherent variances in the standard method that are assumed to be "correct" values. It was indicated by previous discussion herein that the plastic limit point is less clearly defined by the moisture tension method also.

The distinct double modal characteristic of the silty clays indicates the possibility that there are soils within the textural group that have

two distinct sets of characteristics, indicating that divisions within the textural group would have to be made to improve the results. The composition would seem to be suspect; however, visual observations of tabulated values in Table 22 shows definitely that there is practically no difference of composition in the values that deviate 0 or 1 and those that deviate 5 or 6. It would appear that a great deal more study would be required to determine the cause of the variance and to find methods or factors that would compensate for it. In general, the plastic limit results cannot be generally termed "acceptable" based on the available data. However, the method could be used for the determination of plastic limit values for clays and good results should be possible.

One note of caution is in order regarding the results presented herein. It must be remembered that all of the runs at specific pressure were made on Iowa soils. There is no assurance that the pressures presented herein would achieve the same results in a different geological environment. It is possible that it would make little difference; nevertheless, some preliminary determinations should be run.

In regard to preliminary determinations, it has previously been pointed out that the curves were of little value in picking a pressure. Another method is recommended. Instead of plotting several points, make regular runs at several different pressures and calculate the algebraic deviation. Plot this variation against pressure and a line drawn through the points should intersect the pressure axis at the correct pressure.

SUMMARY AND CONCLUSIONS

The objective of this project was to investigate the feasibility of using moisture tension as a practical method of approximating consistency limit values. The first "phase" consisted of obtaining points and plotting moisture tension desorption curves for each textural group. The curves turned out to be of little value in determining usable pressures. However, an evaluation of the curves in light of theoretical concepts of both moisture tension and plasticity, provided a basis to evaluate the soundness of the moisture tension method and showed that a definite relationship existed between the two. Whenever possible, theoretical explanations were given to the curves. In regard to finding specific pressures, trial and error was finally necessary.

After a pressure was determined for each group, 960 consistency determinations were made (687 liquid limits and 273 plastic limits) and the results were tabulated and analysed. A criteria was suggested and the deviations were tabulated.

Conclusions arrived at are as follows:

1. Moisture tension desorption curves follow a predictable pattern for each textural group studied. Although forces other than capillarity play an important role, probably a dominant one in the clays, the composition mainly controls the parameters that affect curve shape.

2. The desorption curve can be divided into three distinct regions. By assuming popularly accepted moisture tension and plasticity theory as being correct, the three regions, "lower flex", "upper flex" and the "unloading region" between the flexes, are analogous to the liquid limit,

plastic limit and plasticity index, respectively. The moisture tension method of liquid limit determination is based on theoretical principles and offers a less empirical, less arbitrary and more clearly defined point than the standard ASTM method.

3. There is essentially no operator variability connected with the moisture tension method. A test indicated that wide variances in initial condition of the soil had little effect on the resulting value; therefore, differences in operator technique should not affect the results, the equipment itself offers no source for variation, and that caused by sampling, or splitting a sample into portions, is minimal.

4. The moisture tension method can be used to approximate liquid limits of Iowa soils with less variance than that of the ASTM standard method at the following pressures:

Clay	40 inches of water pressure
Silty clay	40 inches of water pressure
Silty clay loam	60 inches of water pressure
Clay loam	60 inches of water pressure
Loam	70 inches of water pressure
Sandy loam	70 inches of water pressure
Gravelly sandy loam	70 inches of water pressure
Silt	70 inches of water pressure

5. The effect of textural groups on liquid limit determination is not especially critical; the total pressure difference used being only 30 inches of water or 1.09 psi. Obtaining acceptable results, then, at one pressure cannot be ruled out, although a time factor may be required.

6. The plastic limit value of clay can be approximated at 162 psi and should be within the deviation established herein. However, the rest of the plastic limit groups run were questionable.

7. The limit values obtained by moisture tension can be reproduced at the same tension with little variation; they are reproducible to a

high degree.

8. The quality of the results and the speed of making determinations make the moisture tension method a valuable substitute for liquid limit devices. The method shows such promise that it should be valuable to any organization running values in great number.

9. The plastic limit determination by moisture tension shows enough possibility that it should be studied further.

SUGGESTIONS FOR FURTHER STUDY

On the basis of the present investigation, the following areas of further study are suggested:

1. A more extensive program of running limits at one pressure, such as 60 inches of water for all liquid limits.

2. Groupings other than textural groups should be attempted with the plastic limits.

3. Along with the programs above, the same consistency limit values should be also reproduced by the standard ASTM method so that a more meaningful statistical comparison can be made.

4. "Undisturbed" samples should be investigated as they are obtained; e.g. take a 2 in. core and slice of 1/4 - 1/2 inch "discs" and run in the usual manner.

5. The effect of a time variable should be studied. The operation could perhaps be speeded up by running at higher pressures for shorter times.

BIBLIOGRAPHY

1. Abun-Nur, Edward A. Plastic limit-comparison of cube and standard thread test methods. Symposium on Atterberg limits. ASTM Special Technical Publication No. 254: 212-215. 1959.

2. American Society for Testing Materials. Standard method of test for plastic limit and plasticity index of soils. ASTM Standards. Part 11, Designation: D 424-59. Philadelphia, Penn. Author. 1964.

3. _____. Tentative method of test for liquid limit of soil. ASTM Standards. Part 11, Designation: D 423-61T. Philadelphia, Penn. Author. 1964.

4. Ballard, G. E. H. The plastic limit as a binary packing phenomenon. Materials Research and Standards 4: 366-374. 1964.

5. _____ and Weeks, W. F. The human factor in determing the plastic limit of cohesive soils. Materials Research and Standards 3: 726-729. 1963.

6. Bauer, Edward E. History and development of the Atterberg limits. Symposium on Atterberg limits. ASTM Special Technical Publication No. 254: 160-167. 1959.

7. Baver, L. D. Soil Physics. 3rd ed. New York, N. Y. John Wiley and Sons, Inc. 1956.

8. Bodman, G. B. Methods of measuring soil consistency. Soil Science 68: 37-56. 1949.

9. Casagrande, Arthur. Notes on the design of the Atterberg limits of soils. Geotechnique 8, No. 2: 84-85. 1958.

10. _____. Research on the Atterberg limits of soils. Public Roads 13: 121-136. 1932.

11. Coleman, J. D. and Marsh, A. D. An investigation of the pressure-membrane method for measuring the suction properties of soil. J. of Soil Science 12: 343-362. 1961.

12. Croney, D. and Coleman, J. D. Soil structure in relation to soil suction (pF). J. of Soil Science 5: 75-77. 1954.

13. Darienzo, Michael and Vey, E. Consistency limits of clay, by the vane method. Highway Research Board Annual Meeting Proceedings 34: 559-566. 1955.

14. Davidson, D. T. Effect of certain large organic cations on physico-colloidal properties related to soil stability. Unpublished Ph.D.

thesis. Ames, Iowa Library, Iowa State University of Science and Technology. 1948.

15. _____ and Handy, R. L. Studies of the clay fraction of southwestern Iowa loess. Clays and Clay Minerals Conference Proceedings 2: 190-208. 1953.

16. _____ and Sheeler, J. B. Clay fraction in engineering soils. Highway Research Board Annual Meeting Proceedings 31: 558-563. 1952.

17. Dawson, Raymond F. Investigations of the liquid limit test on soils. Symposium on Atterberg Limits. ASTM Special Technical Publication No. 254: 190-195. 1959.

18. Eden, W. J. Use of a one-point liquid limit procedure. Symposium on Atterberg Limits. ASTM Special Technical Publication No. 254: 168-175. 1959.

19. Fairburn, P. E. and Robertson, Robert H. S. Liquid limit and dye adsorption. Clay Minerals Bulletin 3: 129-136. 1957.

20. Fukuda, Hitoshi. Mechanism of soil moisture extraction from a pressure-membrane apparatus: Water and its conduction in soils. Highway Research Board Special Report No. 40: 73-77. 1958.

21. Gill, William R. and Reaves, Carl A. Relationships of Atterberg limits to some other properties of Illinois soils. Soil Science Soc. of America Proceedings 21: 491-494. 1957.

22. Grim, Ralph E. Applied clay mineralogy. New York, N. Y. McGraw-Hill Book Company, Inc. 1962.

23. _____. Physico-chemical properties of soils: clay mineral. ASCE J. of Soil Mech. and Foundations Div. 85, SM2: 1-17. 1959.

24. Hogentogler, C. A., Terzaghi, Charles and Wintermyer, A. M. Present status of subgrade soil testing. Public Roads 9: 1-8. 1928.

25. _____, Wintermyer, A. M., and Willis, E. A. Subgrade soil constants and their significance and application in practice. Public Roads 12: 89-108; 117-144. 1931.

26. Hovanyi, Paul. A new grooving tool. Geotechnique 7: two unnumbered pages between pp. 78 and 79. 1958.

27. Joslin, J. G. and Kavis, H. E. Ohio adopts the one-point mechanical method for determining the liquid limit of soils. Symposium on Atterberg Limits. ASTM Special Technical Publication No. 254: 178-182. 1959.

28. Kinnison, Charles S. A study of the Atterberg plasticity method.

Bureau of Standards Technical Paper No. 46. 1915.

29. Krebs, Robert D. (Discussion of) Study of the reproducibility of Atterberg Limits. Highway Research Board, Highway Research Record No. 63: 29-30. 1964.

30. Liu, Thomas K. and Thornburn, Thomas M. Study of the reproducibility of Atterberg limits. Highway Research Board, Highway Research Record No. 63: 22-28. 1964.

31. Mickle, Jack LeRoy. Accumulation of moisture in soil under an impervious surface. Unpublished Ph.D. thesis. Ames, Iowa. Library, Iowa State University of Science and Tecnnology. 1960.

32. Mitchell, James, E. Liquid limit results from various types of grooving tools. Symposium on Atterberg Limits. ASTM Special Technical Publication No. 254: 197-202. 1959.

33. McNamara, Edward P. Fundamentals of Ceramics. 2nd. ed. State College, Pa. The Pennsylvania State University Press. 1956.

34. Morris, M. D., Ulp. R. B. and Spinna, R. J. Recommendations for changes in the liquid limit test. Symposium on Atterberg limits. ASTM Special Technical Publication No. 254: 203-211. 1959.

35. Norton, F. H. Elements of ceramics, New York, N.Y. Adison-Wesley Press. 1952.

36. _____. Fundamental Study of Clay: A new theory for the plasticy of clay-water masses. J. American Ceramics Society 31: 236-240. 1948.

37. Odell, T. T. Thornburn, T. H. and McKensie, L. J. Relationships of Atterberg limits to some other properties of Illinois soils. Soil Science Soc. of America Proceedings 24: 297-300. 1960.

38. Plastic limit of soils determination without personal error. Highways and Bridges and Engineering Works 32, No. 1556: p. 10. 1964, Original not available; abstracted in Highway Research Abstracts 34, No. 11: p. 23. 1964.

39. Richards, L. A. Methods of measuring soil moisture tension. Soil Science 68: 95-112. 1949.

40. _____. Porous plate apparatus for measuring moisture retention and transmission by soil. Soil Science 66: 105-110. 1948.

41. _____. A pressure membrane extraction apparatus for soil solution. Soil Science 51: 377-386. 1941.

42. _____.and Fireman, M. Pressure plate apparatus for measuring

moisture sorption and transmission by soils. Soil Science 56: 395-404. 1943.

43. Rollins, R. L. and Davidson, D. T. The relation between soil moisture tension and the consistency limits of soils: Methods for testing engineering soils. Iowa Engr. Expt. Sta. Bull. No. 192: 210-220. 1960.

44. Scott, Ronald F. Principles of soil mechanics. Reading, Mass., Addison-Wesley Publ. Co., Inc. 1963.

45. Seed, Bolton H., Woodward, Richard J., Jr. and Lundgren, Raymond. Clay mineralogical aspects of the Atterberg limits. J. of the Soil Mech. Div., ASCE 90, No. SM4: 107-131. 1964.

46. _____, _____, _____. Fundamental aspects of the Atterberg limits. ASCE J. of the Soil Mech. and Foundations Div. 90, No. SM6: 75-105.

47. Shook, J. F. and Fang, H. Y. A study of operator variability in the determination of liquid and plastic limits of soil. Special Paper, Highway Research Board, Highway Research Abstracts 31, No. 9: 26-28. 1961.

48. Skempton, A. W. The colloidal activity of clays. International Conf. on Soil Mech. and Foundation Engr. Proceedings, 3rd, Zurich, Switzerland 1: 57-66. 1953.

49. Sowers, George F., Vesic, A. and Grandolfi, M. Penetration tests for liquid limit. Symposium on Atterberg limits. ASTM Special Technical Publication No. 254: 216-224. 1959.

50. Sundolf, William Adolf. Effect of wetting time on plasticity indices of eight soils. Unpublished M.S. thesis. Ames, Iowa. Library, Iowa State University of Science and Technology. 1949.

51. Winslow, J. D. and Gates, G. R. Effect os soil rehydration on Atterberg limits. Materials Research and Standards 3: 205-210. 1963.

52. Wintermyer, A. M. Adoption of Atterberg plasticity tests for subgrade soils. Public Roads 7: 119-122. 1926.

53. _____, Willis, E. A. and Thoreen, R. C. Procedures for testing soils for the determination of the subgrade constants. Public Roads 13: 121-136. 1932.

54. Soilmoisture Equipment Co. Instruments for the extraction and measurement of soil moisture. Catalog 60. Santa Barbara, California. Author. (circa 1964).

55. _____. Operating instructions for the pressure membrane extractor, Cat. No. 1000. Santa Barbara, California. Author. (circa 1960).

56. _____. Using the pressure plate extractor. Santa Barbara, California. Author. (circa 1960).

57. Terzaghi, Charles. Determination of the consistency of soils by means of penetration tests. Public Roads 7: 230-247. 1926.

58. _____. Simplified Soil tests for subrades and their physical significance. Public Roads 7: 153-162. 1926.

59. U.S. Corps of Engineers. Simplification of the liquid limit test procedure. WES Technical Memorandum No. 3. 1949.

60. U.S. Dept. of Agriculture. Diagnosis and improvement of saline and alkali soils. Handbook No. 60. 1954.

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